MATERIALS SCIENCE APPRAISAL OF RECYCLED CONSTRUCTION MATERIALS FOR ROADWAYS

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I certify that this thesis is the true and accurate version of the thesis approved by the examiners.

Signed ……………………………………………… Date……………….
(Director of Studies)

DECLARATION

I, Olisanwendu Ikechukwuka Ogwuda, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I can confirm that this has been indicated in the thesis.

Signed ……………………………………………… Date……………….

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ABSTRACT

This thesis reports on a materials science appraisal for recycled construction materials in roadways, that supports engineering decision-making. Inconsistent performance criteria for roadway materials and the variable nature of material source have prompted the need for this research.

The aim of the study is to investigate the application of a materials science appraisal to recycled construction materials for use in roadways. The investigation is undertaken through a literature review of roadways, conceptual development of the materials science appraisal methodology, and demonstration of the application of the materials science appraisal to recycled construction materials; and how this supports engineering decision-making.

The literature review revealed that there are numerous and proven uses of recycled and secondary materials in roadway applications but there was a lack of necessary integration of materials into categories by material-type, which can better describe behaviour in an engineering situation.

Three novel fundamental material types (ceramic, metallic, and polymeric) have been described. The conceptual development of the innovative and novel materials science appraisal, based on material-type, has defined how materials science through a systematic step-by-step procedure can be used to achieve engineering sustainability in roadways and provide support in engineering decision-making.

The application of the novel concept of the materials science appraisal to recycled construction materials is shown through the essence of laboratory testing. The results from the materials science appraisal, together with sensitivity analysis, give an informed engineering decision on product choice.

The appraisal is novel in that it is proposing a new theory on materials science and developed a paradigm shift in the evaluation of recycled construction materials. The appraisal overcomes the absence of materials science thinking in the field of roadway engineering.

The materials science appraisal is of benefit to various stakeholders (client, consultant, supplier and contractor) as it provides a method for addressing material uncertainties. A system now exists for introducing into designs and any contract the principles of the materials science appraisal that will be of great benefit to industry.

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ABBREVIATION

AAS	Aggregates Advisory Service
AASH(T)O	American Association of State Highway (and Transportation) Officials
ACV	Aggregate Crushing Value
AIV	Aggregate Impact Value
APT	Accelerated Pavement Testing
BRE	Building Research Establishment
BS	British Standard
BS EN	British and European Standard
CBR	California Bearing Ratio
C_c	Coefficient of Curvature (curvature coefficient)
CFA	Coal Fly Ash
CIB	International Council for Research and Innovation in Building and Construction
CIRIA	Construction Industry Research and Information Associations
CIT	Clegg Impact Tester
CRCP	Continuously Reinforced Concrete Pavement
C_u	Coefficient of Uniformity (uniformity coefficient)
d_{10}	sieve through which 10% of the material passes
d_{30}	sieve through which 30% of the material passes
d_{60}	sieve through which 60% of the material passes
DCP	Dynamic Cone Penetrometer
DTI	Department of Trade and Industry
EA	Environment Agency (UK)
EC - DGVII	European Commission – DGVII (Directorate-General for Energy and Transport)
ESA	Equivalent Standard Axles
FBA	Furnace Bottom Ash

ABBREVIATION

FWD	Falling Weight Deflectometer
GCCP	Government Construction Client Panel
GDP	Gross Domestic Product
HVS	Heavy Vehicle Simulator
IBAA	Incinerator Bottom Ash Aggregate
MDD	Maximum Dry Density
MS	Materials Science
msa	Million Standard Axles
NAT	Nottingham Asphalt Tester
OECD	Organisation for Economic Co-operation and Development
OMC	Optimum Moisture Content
OPC	Ordinary Portland Cement
PFA	Pulverised Fuel Ash
QH	Quick Hydraulic (hydraulic only binder(s) including cement)
QVE	Quick Visco-Elastic (bituminous and hydraulic binder(s) including cement)
SBM	Slag Bound Macadam
SH	Slow hydraulic (hydraulic only binder(s) excluding cement)
SHW	Specification for Highway Works
SVE	Slow Visco-Elastic (bituminous only or bituminous and hydraulic binder(s) excluding cement)
TFV	Ten percent Fines Value
TRL	Transport Research Laboratory
WSSD	World Summit on Sustainable Development

Chapter 1 Introduction

1.1 Introduction

This chapter introduces contemporary issues in relation to sustainable development, which subsequently leads on to sustainable construction (a subset of sustainable development). The issues and need for this research in relation to sustainable construction – more specifically materials science appraisal of recycled construction materials for roadways – are also presented in this introductory chapter.

1.2 Sustainable Development

There is no universal definition for sustainable development, but all interpretations are good for the environment and for society, as can be seen from some of the following definitions:

1. Improving the quality of human life while living within the carrying capacity of supporting ecosystems (World Conservation Union (IUCN), et al. 1991).
2. Sustainable development means sustainability not only "ecologically" and "economically" but also "socially" and "culturally" (European Commission 2001b).
3. Development which meets the needs of the present without compromising the ability of future generations to meet their own needs; the Brundtland Report (World Commission on Environment and Development 1987).

The debate on sustainable development has been, and is still, ongoing in many areas such as global warming, resource management, economic development, endangered species, sanitation, shelter, food security, health care, education, and globalisation; to list a few. Continuous improvement on a long-term basis is the cornerstone of sustainable development; there is no end point – the starting point being present performance. The increase in awareness of sustainable development has been triggered by many events, some world wide while others entirely localised. In 1992 over 150 countries met in Rio de Janeiro for the UN conference on Environment and Development (the Earth Summit) and agreed on a comprehensive programme (Agenda 21 - Agenda for 21st Century) of more sustainable development throughout the world for the 21st century. The recommendation from the summit was that individual countries prepare strategies and action plans to implement their parts of the agreements (United Nations 1992). In 2002 the World Summit on Sustainable Development (WSSD) was held in Johannesburg, South Africa, in which over 180 countries were represented and the commitment to sustainable development was reaffirmed. It was agreed that the interdependent and mutually reinforcing pillars of sustainable development – economic development, social development and environmental protection – should be advanced and strengthened at the local, national, regional and global levels (United Nations 2002).

In response to the sustainable development aims agreed at the 1992 summit, the UK government produced a strategy on sustainable development titled "Sustainable Development: The UK Strategy" (Department of the Environment 1994). The strategy covered four main areas:

1. Principle and aims underlying sustainable development
2. The environment over a period of 20 years (from the mid 1990s)
3. Economic development and sustainability
4. Putting sustainability into practice.

In May 1999 the UK government produced a further document, in relation to sustainable development, titled "A better quality of life: a strategy for sustainable development". The document set four main aims (Department of the Environment Transport and the Regions 1999a):

1. Social progress that recognises the needs of everyone
2. Effective protection of the environment
3. Prudent use of natural resources
4. Maintenance of high and stable levels of economic growth and employment.

Sustainable development is high on the agenda of the UK, at national and local level, and the construction industry has an opportunity to make a positive impact.

The construction industry contributes one of the main supports (e.g. building and transport infrastructure) of economic development and, conversely, has significant impacts on resources (e.g. land, materials, energy, water) and on the living and working environment. Hence the construction industry has a lot of direct and indirect links with the various aspects of sustainable development.

1.3 Sustainable Construction

Sustainable construction practices and priorities are widely different, depending on how well the concept is developed in various countries. There is also a marked difference between developed market economies, transition economies and developing economies. The more developed economies pay more attention to the creation of a sustainable building stock either by new developments or by upgrading their existing building stock (CIB 1998). In the transition economies the emphasis is on new developments (e.g. to reduce housing shortage), by learning from the experience of developed economies, and making improvements, e.g. to their transport networks. In the developing economies social equity is much higher on the agenda than environmental concerns; social and economic sustainability (e.g. job creation) is given much more thought (Carpenter 2001a, 2001b).

Like the term "sustainable development", sustainable construction means different things to different people in different parts of the world depending on local circumstances. The main emphasis in national definitions lies in ecological impacts to the environment (biodiversity, tolerance of nature and resources), with the problems of poverty and underdevelopment or social equity sometimes being ignored in the definitions of sustainable construction. In addition to economic and social issues numerous other variables (e.g. demography and natural hazards) vary from country to country (CIB 1998).

It has been suggested that perhaps the way to approach sustainable construction is to start from the generic objectives and definitions of sustainable development given in section 1.2, above (CIB 1998, European Commission 2001b). From this starting point a more concrete definition of the concept of sustainable construction can be developed from issues of sustainable development that relate to the construction sector. Consequently, definitions of sustainable construction would relate to sustainable development, with a built environment theme.

Reaching consensus on the exact meaning of a sustainable construction concept may not be quite so easy as has been demonstrated in a project involving countries from Europe, Asia and USA (CIB 1998). However, the paradigm put forward in this thesis is about the efficient use of resources, which is included within all definitions on sustainable construction. A few definitions from the literature are given below:

1. Sustainable construction is the set of processes by which a profitable and competitive industry delivers built assets (buildings, structures, supporting infrastructure and their immediate surroundings) which (GCCP 2000):
   (i) enhance the quality of life and offer customer satisfaction
   (ii) offer flexibility and the potential to cater for user changes in the future
   (iii) provide and support desirable natural and social environments, and
   (iv) maximise the efficient use of resources
2. The creation and responsible management of a healthy built environment based on resource efficient and ecological principles (Kibert 1994). This is the definition introduced at the first international conference on sustainable construction held in Tampa in 1994.
3. Sustainable construction is about the construction industry contributing to sustainable development by (Department of the Environment Transport and the Regions 2000)
   (i) being more profitable and more competitive
   (ii) delivering buildings and structures that provide greater satisfaction, well-being and value to customers and users
   (iii) respecting and treating its stakeholders more fairly
   (iv) enhancing and better protecting the natural environment, and
   (v) minimising its impact on the consumption of energy (especially carbon-based energy) and natural resources.

In summary, sustainable construction appears to be about the provision of infrastructure that improves the quality of life, e.g. provides safe and secure buildings for people to live and work in and provides roads and other transportation infrastructure to enable people to travel for business and pleasure. The industry itself has to work in a sustainable way, by prudent and economic management of resources, by minimising energy consumption, by reducing pollution and waste, by job provision, and by valuing its workforce.

The outputs of the construction industry are predominantly investment goods – infrastructure that others use in the creation of goods and services. Construction infrastructure is vital to people's survival and welfare, as people spend an average of around 80% of their time in buildings or on roads (European Commission 2001a). Buildings provide shelter, protection, privacy, comfort and warmth (housing); education (schools, universities); culture (theatres, concert halls); business (factories, offices); healthcare facilities (hospitals); and pleasure (leisure and sports centres). Transportation infrastructure enables people to travel for business and pleasure. The transportation infrastructure also provides an opportunity for goods and services to be moved from place to place, and other economic benefits such as higher property values and increased productivity.

Hence it could be argued that the construction infrastructure enhances the quality of life and provides customer satisfaction, and enhances desirable natural and social environments; but there are concerns regarding the efficient use of resources. There are concerns with the large amounts of waste from construction and demolition processes, and the quality of ground, air and water from emitted pollutant gases, dust and liquids (European Commission 2000). A recent report has attempted to identify and quantify (by mass) the natural resources (materials and energy) used, waste generated and emissions to air by the UK construction industry. The report concluded that reduction in all three areas would improve resource sustainability (Smith, et al. 2002).

Environmental issues are a growing concern around the world. More attention is being paid to the adverse environmental impacts of roads. Environmental impact assessments are now obligatory for all projects with potentially significant adverse impacts and is usually tied in to some form of public consultation (World Bank 2001). Environmental taxes (e.g. on pollution, transport, energy, resource use, CO_2 emissions) are sometimes used as an instrument for achieving more sustainable construction. The object of these taxes is to include external environmental costs in prices so producers and consumers have an incentive to limit environmental pollution and to treat natural resources more responsibly. They should not necessarily be interpreted as an indicator of environmental friendliness.

Means of reducing the amount of primary (virgin) materials extracted, increased recycling of materials, and waste management are high up the agenda of many countries (Lewis 2004, Reid, et al. 2001, United Nations 2002). Current issues regarding the consumption of primary materials, the amount of waste generated and environmental concerns are being expressed more explicitly and freely.

1.4 Rationale for a Novel Concept in Materials Science Appraisal

Major construction customers have global businesses and global reference points. They are informed and more demanding of construction services and products. It is gradually becoming a condition of service for any “business partnership” for the relationship to add value to the client’s downstream operations and on occasion to share the risk involved in those ventures, perhaps even to take an equity stake as well. Above all customers expect that the companies that they do business with to understand and meet their objectives (Heggie and Vickers 1998, Simmonds and Clark 1999). The industry will have to adapt to emerging construction markets, which have environmental and social dimensions. Construction businesses are expected to integrate into, and consider more fully the issues valued at national, regional and local community level where the driving forces are a mixture of political, social and market forces, requiring products which respond to genuine need and concerns (CIB 1998, Saxon 2002).

For most groups of customers in the UK and continental Europe, a “faster faster” scenario is likely to hold, with businesses having to work harder to maintain levels of growth and profitability. As part of this intensification all businesses will work their assets harder and that will include buildings and other civil engineering infrastructure; assets must deliver more value (Griffin, et al. 2000, Simmonds and Clark 1999).

The changing environment for road pavement construction and maintenance will require clients to have at their disposal a range of engineering solutions and tools to assist with their decision-making processes. The choice has to suit present and future economic and environmental circumstances, enable cost-effective road construction and maintenance, and relate to the wider regional development objectives (Griffin, et al. 2000). Road pavement engineers should provide pavement systems that will perform functions in the most effective and sustainable way.

In road construction and maintenance the use of performance criteria, and a move away from traditional recipe specifications, is the way forward – there is worldwide evidence that this is happening (World Bank 2001). With the gradual move towards performance criteria:

1. There should not be a need to unduly discount good material
2. Materials can be applied to their highest capability in the road pavement
3. Thinner pavement layers can be employed.
4. There is flexibility for using the best options for different circumstances.

The implementation of improved technology must also continue in line with the increase in performance requirements driven by changes in traffic and availability of new materials.

Road pavements are expected to perform under increasingly severe conditions, such as greater tyre contact stresses, loads, and load repetitions, including changes resulting from advancements in tyre technology (Epps, et al. 2000). Choice of materials to meet pavement performance requirements has to be wide-ranging, hence demands of combinations of strengths and layer thickness, which may limit choice, may not be suitable (Merrill, et al. 2004).

Comparison of road materials and techniques and specifications should be based on a technical evaluation of materials in conjunction with economic and environmental assessments, and should normally include any taxes and subsidies that are available (e.g. vehicle operating costs, CO_2 emissions, landfill). A level "playing field" should be used when analysing products, be it primary, secondary or recycled materials – analysis should be based on “fit-for-purpose” materials. Consideration of recycled and secondary products should be based on the same technical rules that are applied to primary materials. The problem is not the origin of the material but a failure to understand its properties and how it will behave in an engineering situation (OECD 1997, Reid and Chandler 2001, Symonds Group Ltd, et al. 1999). While there is agreement on the need for appropriate performance criteria, in this respect, there is a difference of opinion in the construction industry as to whether such criteria (e.g. leaching) need to be developed specifically for recycled and secondary materials only or all materials irrespective of their source (Symonds Group Ltd, et al. 1999).

An additional requirement, and equally important, is an understanding of the underlying theory regarding road materials and their performance. It has been stated that the man of construction will contently walk into a building, designed according to the theories of structural mechanics, without fearing its collapse – true innovation cannot come about without 'know-why' (Koskela 2002). The underlying theory may need to be adapted or advanced, and, consequently, systems, tools and practices developed. New ideas are required to advance the technologies needed to meet the present and future demands of customers.

Continuous research and development, including current and innovative materials (and technologies), is essential for the UK construction industry as a whole as highlighted in the Fairclough review into rethinking construction innovation and research – the review not being too dissimilar from similar reviews in other countries; many of the detailed recommendations of the Fairclough review relate specifically to UK issues, but the broad theme has international relevance (Courtney 2002, Department of Trade and Industry 2002, Lansley 2002). Collaborative research and development and its exploitation has formed the basis for a recent £250,000 collaborative research and development award from the UK Government Department of Trade and Industry (DTI) to a consortium comprising the Author's organisation and forward-thinking industrial partners. The technology aspect of the award is partly being developed from the product of this PhD thesis.

1.5 Research Aim

The research aim is to investigate the application of a materials science appraisal to recycled construction materials for use in roadways. This is to be achieved through the following objectives:

1. To develop a materials science concept for application in roadways.
2. To use the concept to develop the materials science appraisal.
3. To evaluate the robustness of the materials science appraisal.

1.6 Research Hypothesis

The hypothesis of the research is that the proposed materials science appraisal of recycled construction materials for use in roadways is a rational mechanism for supporting engineering decision-making in road construction and maintenance.

1.7 Research Methodology

The first stage of the research methodology comprised a literature review which enabled an evaluation of the performance requirement issues in relation to road pavement materials; these include road pavement structure, materials technology, analysis, testing and design.

The second stage involved conceptual development of the materials science appraisal methodology. The development was based on proposing new material-type theories from old theories. This enabled subsequent development of the methodology.

The third stage involved application of the materials science appraisal methodology based on reviewed literature and experimental work; and demonstration of how the appraisal can support engineering decision-making.

1.8 Structure of Thesis

This thesis has a further six chapters which examine the issues concerning road pavement materials science and related performance criteria. The structure of the thesis is presented as an argument, as shown in Figure 1.1.

A review of recycled and secondary materials for use in roadways is presented in Chapter 2. Literature review and critique on roadways are detailed in Chapter 3. Conceptual and appraisal development are presented in Chapter 4. Application of the appraisal technique is given in Chapter 5. An integrated evaluation of the appraisal is given in Chapter 6, and conclusions and recommendations for future work are presented in Chapter 7.

Appendices are presented which contain additional information in support of the study. Publications arising from the work are also included in the appendices.

1.9 Summary

The sustainable development and sustainable construction perspectives (including a brief overview of diverse priorities in developed, transition and developed countries), which relate to the research study presented in this thesis, have been highlighted in this chapter. The rationale for the need for consistent performance criteria for road pavements have been highlighted. This is related to customer needs and the variable nature of material source – the use of unbiased performance criteria, underpinned by materials science and robust theoretical principles, is a way forward.

The focus of the PhD research study is on using materials science ‘know-why’ to undertake performance appraisal of recycled materials for use in roadway applications.

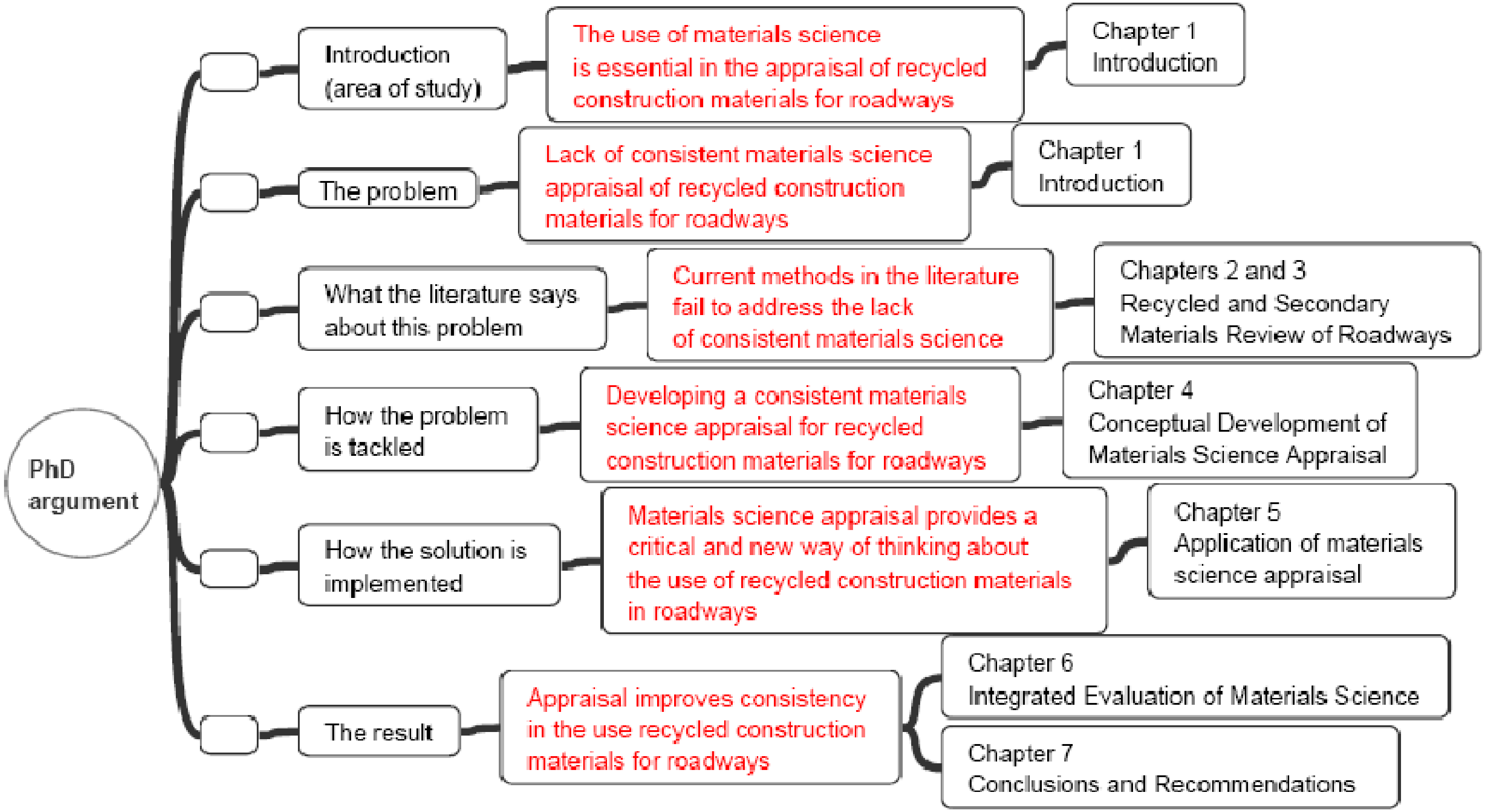


Figure 1.1: Structure of thesis, adapted from Easterbrook (2003)

Chapter 2 Recycled and Secondary Materials in Roadways

2.1 Introduction

Worldwide there is pressure to increase the use of recycled and secondary materials in construction applications such as roads. This is reflected in the waste management hierarchy which is generally summarised as (OECD 1997, Reid, et al. 2001, Symonds Group Ltd, et al. 1999):

1. Prevention or avoidance of waste.
2. Reduction or minimisation of: (i) waste and (ii) the use of natural resources.
3. Recycling of materials in parent industry at the highest possible technical level.
4. Recycling of materials from other industries.
5. Incineration (for energy recovery) and to reduce volume of waste to landfill.
6. Disposal in a safe manner, usually to landfill.

The use of recycled and secondary materials in road construction contributes directly to options 1 to 4, by reducing the amount of natural aggregate consumed and recycling materials that would otherwise be disposed of as waste. The use of recycled and secondary materials enables the products of option 5 to be recycled in road construction and reduces reliance on option 6.

The extraction of primary materials is of major concern, not only due to depletion of non-renewable resource but also due to associated environmental impacts such as loss of mature countryside, change in ecosystem (e.g. where aggregate is extracted), visual intrusion, noise (e.g. from heavy vehicles), dust and blasting vibration. The disposal to landfill sites of recoverable materials also has environmental impacts that arise from transportation, from possible leaching of the material at landfill sites, and from reduction in the number of landfill sites available for non-recoverable wastes. In this context, the road construction and maintenance industry is a user of two types of natural resources – mineral resources (e.g. aggregates, cement, and bitumen) and energy; and in the process generates waste and pollution.

Hence, an area that has developed considerable interest is the reuse of recycled and secondary materials. The use of recycled and secondary materials is feasible and has been proven in many cases, with some recycled and secondary materials (e.g. recycled crushed concrete) outperforming primary materials (De Urbina and Goumans 2003, Dhir, et al. 2003, Edwards 2003, Eighmy 2003, Goumans, et al. 1997, Goumans, et al. 1994, Hansen 1992, Lauritzen 1994, OECD 1997, Reid, et al. 2001, Sherwood 2001, The Highways Agency (England), et al. 2001a, Woolley, et al. 2000).

However, rational engineering decision-making has to be used in the application of these materials. The following sections (2.2 to 2.12) describe some recycled and construction materials that have a proven use in roadway applications; but decisions for their use are generally based on fit-for-purpose applications with little understanding of the underpinning materials science.

2.2 Baghouse Dust

Baghouse dust are particles that are captured from the exhaust gases of asphalt mixing plants. Secondary collection equipment called baghouse are used to collect these very fine sized materials. Baghouse dust is recycled within asphalt plants as filler. Around 80-90% of baghouse dust is recycled. Material has a particle size generally ranging from 0.01 mm to 0.6 mm, with a specific gravity of approximately 2.7 (Chesner, et al. 2002).

2.3 Blast-furnace Slag

Blast-furnace slag is a by-product from the manufacture of pig-iron from iron ore. Iron ore (a mixture of the oxides of alumina, silica and iron) is reduced to iron by chemical reactions which take place in the furnace while the oxides of alumina and silica combine with the fluxing stone (limestone and dolomite) to form blast-furnace slag. The blast-furnace slag settles on top of the molten iron from where it is subsequently run off and cooled by air, water or a combination of air and water.

Air-cooled blast-furnace slag is the most common blast-furnace slag used in road construction and is suitable as a material for selected granular fill, granular capping, sub-base material, and bound layers. Caution is required where the slag is used below water and below PFA due to problems that may arise with corrosion and drainage (OECD 1997, The Highways Agency

(England), et al. 2001b). Expanded or pelletised slags are used primarily in lightweight structural concrete and masonry units.

In cold countries (e.g. Canada, Finland and Sweden) it has been observed that blast-furnace slags used higher up in the pavement layers tend to cause icing on the road surface. Hence in Sweden there are restrictions on their use in these layers. Leaching problems (e.g. lime and sulphur) may occur with blast-furnace slags. This is not a potential problem as long as the slags contain less that 1% sulphur, which is usually bound up within the aggregate. In the UK, at least 100 million tonnes of unbound blast-furnace slag has been used in construction with very few cases of environmental pollution (Dunster 2001). Thermal insulation of slags implies thinner thickness of pavement, which saves on the amount of natural aggregates that are used (OECD 1997).

Slag bound macadam (SBM) is a relatively new technology that uses granulated blast furnace slag activated with a lime-based catalyst as binder for primary and non-primary aggregates. The resulting mixture is potentially suitable for a range of uses within road pavement construction and maintenance, such as a base and sub-base, and also for use as sub-base on weak subgrades (The Highways Agency (England), et al. 2001b). SBM is a cold-lay mix that develops a similar level of stiffness and strength to conventional bitumen and cement-bound material, but at a slower rate – may take up to a year to achieve full strength. This may have implications for design of heavily trafficked roads. The achievement of comparable levels of stiffness and strength is dependent on the mixture being at a moisture content that is compatible with compaction by rolling – usually at or close to optimum moisture content (The Highways Agency (England), et al. 2001c). Due to its characteristics, SBM has extended handling and construction time (can be workable for up to four days), and there are no curing or non-trafficking periods needed during construction. The material exhibits a reduced risk of reflective cracking when compared to cement-bound materials and there is a reduced risk of frost heave when compared to sub-base materials (Department of the Environment Transport and the Regions 1999b).

2.4 Cement Kiln Dust (CKD)

Cement kiln dust (CKD) is a fine powdery material similar in appearance to Portland cement. Fresh cement kiln dusts can be classified as belonging to one of four categories, depending on the kiln process employed and the degree of separation in the dust collection system. There are two types of cement kiln processes: wet-process kilns, which accept feed materials in a slurry form; and dry-process kilns, which accept feed materials in a dry, ground form. In each type of process the dust can be collected in two ways: (1) a portion of the dust can be separated and returned to the kiln from the dust collection system (e.g., cyclone) closest to the kiln, or (2) the total quantity of dust produced can be recycled or discarded.

The chemical and physical characteristics of CKD that is collected for use outside of the cement production facility will depend in great part on the method of dust collection employed at the facility. Free lime can be found in CKD, and its concentration is typically highest in the coarser particles captured closest to the kiln. Finer particles tend to exhibit higher concentrations of sulfates and alkalis. If the coarser particles are not separated out and returned to the kiln, the total dust will be higher in free lime (since it will contain some coarse particles). CKD from wet-process kilns also tends to be lower in calcium content than dust from dry-process kilns.

2.5 China Clay Wastes

The majority of china clay (kaolin) is produced in England (Devon and Cornwall) and in the USA (North Carolina and Georgia) by processes of quarrying and separation (Sherwood 2001). For each tonne of china clay produced, approximately 9 tonnes of waste is produced typically made up of

- 2 tonnes of overburden
- 2 tonnes of waste rock
- 3.7 tonnes of coarse sand waste
- 0.7 tonnes of micaceous residue

The above wastes are usually tipped on adjacent land that is less suitable for china clay workings. With the exception of the micaceous residue, all the waste materials have potential for use as a road construction material. The coarse sand waste has the most desirable engineering properties in terms of composition and gradation.

2.6 Colliery Spoil (Colliery Shale)

Colliery spoil is a waste product from coal mining and is obtained either from clearing out coal pit faces in order to gain access, or from within the pit with the coal (the spoil from within the pit is separated from the coal at coal cleaning plants). Spoils from the coal pit faces and the coal pit are usually dumped on the same spoil heaps hence there is great variability in composition.

Colliery spoil is available in two forms in coal mining areas: (1) unburnt spoil also referred to as unburnt shale, or minestone, and (2) burnt spoil also referred to as burnt shale (derived from spontaneous combustion of the unburnt spoil in spoil heaps). These two forms differ considerably in their chemical and physical condition with the burnt spoil having better chemical and physical properties.

2.7 Construction Arisings

Construction and demolition arisings have been proven to have a very high recovery potential, as shown by pilot projects in member states of the European Union (European Commission 2000). Construction arisings includes crushed concrete, crushed hydraulically bound mixtures (e.g. lightly bound cement mixtures and concrete), bituminous mixtures, crushed brick, crushed block, crushed stones; and possibly a mixture of two or more of these materials.

Crushed concrete can be used as a replacement for primary aggregates for most purposes in the road pavement. Concrete from the demolition of buildings is likely to be reinforced and thus crushing is generally more difficult when compared with the crushing of plain concrete. Building demolition rubble may also be contaminated with other materials such as glass, wood, plaster, paint, insulation, plastic, and metals. Crushed cement bound materials from sub-base layers in the pavement can be re-used as granular sub-base materials or re-stabilised with cement to produce a cement stabilised material. Bituminous mixtures are usually recycled back into bituminous mixtures with the process of recycling covering any depth from the bituminous pavement surface to full depth reclamation of all the bituminous layers. The use of crushed bricks would depend on the type of brick, type of mortar, and on the location in (and type of) the pavement. Crushed bricks in most cases could be used as bulk fill in pavements. Building stone has generally been used as bulk fill material. Other demolition debris may be used as general bulk fill although care must be taken to avoid any timber as this could rot and eventually lead to cavities in the fill.

2.8 Incinerator Refuse

Incinerated fly ash and bottom ash are residues from incineration of household wastes (e.g. glass, clinker, ceramics, metal, paper, rag, food, and packaging). Incinerator ash may contain heavy metals (e.g. from batteries) and other hazardous components. Concerns have been raised about leaching of heavy metals in incinerator fly ash (OECD 1997). There have also been environmental concerns about mixing the fly ash and bottom ash from the incineration process; hence it is preferable to use incinerator bottom ash (IBA) on its own. Recent investigations have shown that incinerator bottom ash is not a problem, although the flue ash tends to contain contaminants/impurities (e.g. dioxins) (Winter 2003).

The main use of IBA is as bulk fill. It can also be used for road pavements from sub-base right up to the surface course. Its use in bound materials has previously not been advised since it may contain aluminium, heavy metals and glass that may react with the binder. On the other hand, bound IBA has been used successfully in some bound mixtures. In the Netherlands incinerator fly ash is partially used as filler in bituminous mixtures; the remainder being dumped in a controlled manner. In Denmark bottom ash is used as granular sub-base. Both these countries require that tests for composition and leachates be carried out. The use of IBA is in its infancy in the UK, but is well established in the Netherlands, Denmark, France, Germany (Edie 2002).

2.9 Pulverised Fuel Ash (PFA) and Furnace Bottom Ash (FBA)

Pulverised fuel ash (PFA) and Furnace bottom ash (FBA) are produced from coal fired power stations. PFA (or “fly ash” as it is known in many parts of the world) is precipitated, either electrostatically or mechanically, from the flue used to carry out the gases from the furnace. FBA is the coarser fractions of the pulverised coal ash that falls and is collected at the bottom of the dry-bottom furnace and sinters (boiler slag is collected at the bottom of wet-bottom furnaces). PFA accounts for about 75-85% of the coal ashes.

The mechanical and electrical precipitates of PFA are initially collected in hoppers and this ash material is known as hopper ash – the ash can be obtained as a dry (white) powder. If the hopper ash is deliberately passed through a mixer-conveyor plant so that a measured amount of water is added before stockpiling, then it is described as conditioned PFA. Water is added in conditioned PFA to prevent dust problems and aid compaction when used for fill. The PFA may be mixed into a slurry and transported hydraulically to storage ponds or lagoons – this material is known as lagoon ash. Furnace bottom ash (FBA) may be sluiced out to lagoons in conjunction with the hopper ash and separation of the coarse from the fine particles of the mixed material takes place during settlement in the lagoons. These types of lagoon ash are, consequently, coarser and more variable.

The main compounds in the pulverised coal ashes are the oxides of silicon, aluminium, and iron. PFA consists of reactive glassy spheres that makes up about 60 – 90% of the PFA, with some crystalline matter and a varying amount of porous and irregular carbon particles. Rapid cooling of the ash from the molten state as it leaves the flame causes PFA to be predominantly non-crystalline (glassy) with minor amounts of crystalline constituents. The crystalline constituents are not generally involved in pozzolanic and/or cementitious activities. Lime may occur alone or in combination with other ingredients in the ash. Residual unburnt carbon and unfused ash minerals may also be present. The colour ranges from almost cream (light brown) to dark grey and is affected by the proportions of carbon, iron and moisture (the greater the carbon content the darker the PFA).

Alumino-silicate PFA (Class F fly ash in the USA), generally have a low lime content (less than 10%) and are produced from bituminous coal and from anthracite. Reactions of alumino-silicate PFA requires high alkalinity of the pore water. Another variety of PFA, known as sulpho-calcitic PFA (Class C fly ash in the USA), is produced from burning sub-bituminous and lignite coal, which both have a high limestone and sulphur content. Sulpho-calcitic PFA have a high lime content (greater than 10%) and hence have relatively good hydraulic cementitious properties that are superior to alumino-silicate PFA (Jackson and Dhir 1996, Sherwood 1995b). PFA can be mixed with lime or cement to activate pozzolanic and cementitious reactions. PFA can also be stabilised with lime or cement in the production of artificial aggregates.

The main uses of PFA have been in cement and concrete, road construction (stabilised capping and sub-base layers), backfill to structures, bulk fill in construction sites, cellular (aerated) concrete and in lightweight aggregate and brick. The utilisation of PFA in concrete has been the most extensive and widespread throughout the world compared to other uses (Manz 1999).

FBA is used as fill, granular (unbound) sub-base material, and in embankments. There is the potential to use FBA as drainage material or free-draining fill, but with some restrictions on the leaching of trace metals (e.g. pyrite). Heavy compaction efforts may lead to break down of FBA particles, but research has shown that the stability of FBA after compaction is satisfactory and thus makes it suitable for minor roadworks (Dawson and Bullen 1991). The high absorption of FBA may lead to higher bitumen requirements in bituminous mixtures. Boiler slag, on the other hand, is a glassy material with low absorption and hence does not require high bitumen content. FBA is rarely used in road construction nowadays as most of the material is generally used in the manufacture of building blocks. Boiler slag is not used widely except in the USA.

2.10 Slate Waste

The majority of slate waste is stockpiled in Wales from the production of roofing tiles (for every tonne of roofing slate produced approximately 10 tonnes of slate waste is produced). Slate waste is chemically inert thus, apart from its flakiness, is suitable as crushed rock provided it meets the requirements for gradation, strength, plasticity and durability. Slate waste can be used as high quality sub-base, bulk fill, selected granular fill and as granular capping material (The Highways Agency (England), et al. 2005).

2.11 Spent Oil Shale

Spent oil shale is the waste material from oil extraction mainly in Scotland. Although the oil extraction in Scotland has ceased, within the areas (West Lothian) that the spent oil shale is heaped there are relatively large amounts. Spontaneous combustion, as with burnt colliery spoil, occurs in the spent shale heaps hence its properties (chemical and physical) are similar to that of burnt colliery spoil.

Current British specifications allows the use of spent oil shale in many roadway applications except its use in bitumen bound and concrete layers (The Highways Agency (England), et al. 2005).

2.12 Steel Slag

Steel slag manufacture involves the removal of excess quantity of carbon and silicon from iron by oxidation and the addition of small amounts of other compounds that are necessary for imparting special properties to the steel. The major problem with steel slag is that they contain free magnesium and/or calcium oxides which on hydration are liable to expand causing the onset of disintegration of the slag particles. Except for these oxides, steel slag is basically a stable material. Thus, the use of steel slag may be restricted to the upper bituminous layers of the road pavement. However, it is also used in granular (unbound) bases, fill and embankments in countries such as the Netherlands, UK, Finland and the USA. Leaching problems (e.g. lime) may occur with unbound steel slags. Crushed steel slags appear like ordinary aggregates, although porous particles may be contaminated. The angularity, higher density, superior frictional (abrasion) resistance and high shear resistance of the steel slag particles make it very suitable as an aggregate in pavement surface layers, although the high density and correspondingly low yield make them economically unattractive (OECD 1997).

2.13 Potential Uses of Recycled and Secondary Materials

As the specification requirements for any given road pavement layer generally tends to be higher than the layers beneath then the use of recycled and secondary material, as replacements (or partial replacements) for primary materials, tends to decrease from bottom upwards in the pavement. Hence, bulk fill has the biggest potential for use of recycled and secondary materials while few of such materials will be used in the surface (Sherwood 1995a).

The potential uses of some recycled and secondary materials are given in Table 2.1. What Table 2.1 shows is the proven uses of these materials in roadway applications, but their application can be better categorised by material-type and how that material-type would behave in an engineering situation; a novel categorisation and material science appraisal system is described in detail in Chapter 4.

Table 2.1: Potential uses of recycled and secondary materials in highway construction, adapted from the Highways Agency (England), et al. (2005)

Application and series ► / Material ▼	Embank-ment and Fill 600	Capping 600	Unbound Mixtures for Sub-base 800	HBM for Sub-base and Base 800	Bitumen Bound Layers 900	PQ Concrete 1000
Blastfurnace Slag	✔	✔	✔	✔	✔	✔
Burnt Colliery Spoil	✔	✔	✔	✔	x	x
China Clay Sand/Stent	✔	✔	✔	✔	✔	✔
Coal Fly Ash /Pulverised Fuel Ash (CFA/PFA)	✔	✔	x	✔	✔	✔
Foundry Sand	✔	✔	✔	✔	✔	✔
Furnace Bottom Ash (FBA)	✔	✔	x	✔	x	x
Incinerator Bottom Ash Aggregate (IBAA)	✔	✔	✔	✔	✔	✔
Phosphoric Slag	✔	✔	✔	✔	✔	✔
Recycled Aggregate	✔	✔	✔	✔	✔	✔
Recycled Asphalt	✔	✔	✔	✔	✔	✔
Recycled Concrete	✔	✔	✔	✔	✔	✔
Recycled Glass	✔	✔	✔	✔	✔	✔
Slate Aggregate	✔	✔	✔	✔	✔	✔
Spent Oil Shale/Blaise	✔	✔	✔	✔	x	x
Steel Slag	✔	✔	✔	✔	✔	✔
Unburnt Colliery Spoil	✔	x	x	✔	x	x

Key:

✔ Specific (permitted as a constituent if the material complies with the Specification (SHW)) or General Provision (permitted as a constituent if the material complies with the Specification (SHW) requirements but not named within the Specification (SHW)).

x Not permitted.

HBM Hydraulically Bound Material.

Recently, in the UK, an investigation has been undertaken into the use of low energy road maintenance covering a range of techniques (in-situ and ex-situ) and materials, such as slag (basic oxygen slag, granulated blast furnace slag and ground granulated blast furnace slag), foamed bitumen and bitumen emulsions. The outcome from the investigation has produced a guide for the use of these materials (Merrill, et al. 2004). A material classification system was developed to handle the potentially large number of material combinations available for cold recycling applications. Four classes were selected based on the speed of curing (quick or slow), depending on the presence of cement, and whether or not the material contained asphalt binder. These material classes were defined as follows:

1. Quick hydraulic (QH) with hydraulic only binder(s) including cement
2. Slow hydraulic (SH) with hydraulic only binder(s) excluding cement
3. Quick visco-elastic (QVE) with bituminous and hydraulic binder(s) including cement
4. Slow visco-elastic (SVE) with bituminous only or bituminous and hydraulic binder(s) excluding cement.

The use of blends of crushed concrete and crushed asphalts can produce a material where the bitumen provides lubrication. This reduces the effort required to compact the material during construction and, under the action of traffic, the crushed concrete/asphalt blend can be stronger than crushed concrete on its own, possibly due to the cohesive effect of the bitumen. Also the blend can provide better resistance to prolonged static loads than pure bituminous mixtures because of the relatively lower proportion of bitumen in the blend. The presence of bitumen even in small quantities apparently changes the blend from predominantly brittle to more ductile (Lauritzen 1998). Blending two or more components provides a composite material that reflects the nature of the individual components, and the principle can be extended to any blended material (primary, secondary and recycled materials).

In the EU, the road construction sector recycles 45 to 100% of its own materials (Carpenter 2001b, OECD 1997, Symonds Group Ltd, et al. 1999). However, a large volume of recycling should not, on its own, be seen as a means to an end. Although there is great potential for recycling in road pavements it should not be seen as a dumping site – road pavements must, first and foremost, perform their pavement structural and surface function. To achieve more sustainable road construction, recycling in road pavements should aim for the highest (optimal) technical use of a material based on structural requirements, economics and environmental constraints.

It should be noted that recycling is not an absolute solution to dwindling resources and pollution but it can extend the life of non-renewable resources by reducing the need for mining, felling or extraction of natural resources. The demand for materials for particular uses also needs to be put in context. Even if all potential recyclable materials were recycled, the quantities are such that they would only meet a comparatively small proportion (currently, under 10%) of the demand for construction materials (Symonds Group Ltd, et al. 1999). Primary materials will therefore continue to have to meet the bulk of the demand for the foreseeable future. However, the decision-making process should be based on a materials science appraisal of potential suitable materials.

Various issues such as specifications, test methods, reliability and quality control, environmental concerns, planning, supply and demand, economics, and lack of awareness have been identified as important for recycling in transport infrastructure (see Table 2.2), with the biggest problem being lack of awareness (Reid and Chandler 2001). One solution to this lack of awareness would be a materials science appraisal system that evaluates performance based on material-type and not material source.

Table 2.2: Summary of Issues relating to Recycling in Transport Infrastructure (Reid and Chandler 2001)

Issue	Description	Available Guidance	Recommended Action Required
Specifications	Some materials and methods are excluded from existing Specifications	A number of Specifications for alternative materials and methods are available	Update existing Specifications to accommodate new developments more quickly, or write new Specifications for particular applications
Test methods	Existing test methods developed for natural materials are not suitable for some alternative materials	A number of tests have been assessed as suitable for alternative materials	Move to performance-based test methods and Specifications
Reliability and Quality Control	Alternative materials perceived as highly variable and of low quality	Utilise or adapt existing quality control systems to produce a consistent, fit-for-purpose material	Demonstrate quality of materials produced under a quality plan, upgrade processing plant to produce higher quality material

Table 2.2: Summary of Issues relating to Recycling in Transport Infrastructure (Reid and Chandler 2001)

Issue	Description	Available Guidance	Recommended Action Required
Environmental Concerns	Potential long term leaching of contaminants into controlled waters; dust and noise during construction	Assess behaviour using leaching tests and existing models where necessary; CDM/COSHH legislation	Agreement between environmental regulators and material producers on use of materials in construction
Waste Regulation including Waste Management Licensing and PPC Regime	Unclear whether materials are waste or covered by exemptions, potential long time scale required by waste permitting processes	Use available guidance on waste permitting system	Approach environmental regulators for advice at early stage in design of project. DEFRA are reviewing exemption system to ensure alternative materials can be used in construction
Conditions of Contract	Some forms of contract may create an environment where there is no incentive for innovation	Use appropriate forms of contract and adopt partnering	Review standard conditions of contract to rectify any clauses discriminating against innovative materials or methods
Planning	Difficulties getting planning permission for recycling centres in or near urban areas	Guidance for planners and applicants has been produced by DETR	Ensure an adequate supply of recycling centres is available to meet local needs
Supply and Demand	Difficulty in matching supply and demand for some alternative materials	Plan in advance and stockpile material if necessary; use existing databases to source materials	Develop long term partnering agreements to enable better prediction of material requirements
Economics	Alternative materials and methods may be more expensive than conventional ones	Ensure comparing like with like; use whole life costing to ensure best practicable environmental option selected	Adjust aggregates levy and landfill tax as necessary to ensure alternative materials remain competitive
Lack of Awareness	Many individuals and organisations unaware of the possibilities, or only aware of potential problems	Disseminate existing information from CIRIA, EA, TRL, BRE, AAS and others	Develop strategies to reach resistant sectors of industry and infrastructure owners

2.14 Summary

To further the advancement of recycled and secondary materials worldwide, all countries – regardless of their current good practices – should continue to explore new opportunities, advance technical knowledge, and design increasingly effective programmes. A large volume of recycling should not on its own be seen as a means to an end and recycled and secondary materials should aim to be used near the source of production and not necessarily in roads with low traffic volumes. Useful recommendations have been provided by the OECD (1997) to encourage the use of recycled and secondary materials:

1. Test materials before recycling.
2. Ensure that materials are used wisely.
3. Promote the increased use of proven solutions.
4. Balance regulations and policies that foster recycling and use of secondary materials, and discourage dumping.
5. Balance engineering, environmental and economic factors.
6. Increase research and knowledge transfer.

These are all acknowledged by the author as being essential, but Chapter 3 focuses on the review of roadways in relation to materials, pavement structure, materials testing and design – and critiques the literature for the materials science appraisal.

Chapter 3 Review of Roadways

3.1 Introduction

To set a detailed technical background for this thesis, this chapter presents a literature review and critique on roadways. In particular the review highlights how consistent materials science appraisal can underpin engineering decision-making for roadways and the lack of this consistency. The broad issues, i.e. road pavement structure and materials technology, related to road pavement performance have been addressed in this chapter. This will enable development of the materials science appraisal, which is presented in Chapter 4.

3.2 Stakeholders

Various stakeholders can be involved in engineering decision-making in road construction and maintenance schemes. However, the stakeholders can be simplified into four broad groups, namely client, consultant, supplier and contractor (Atkinson 1997, Reid and Chandler 2001). Brief descriptions of these groups are as follows:

1. **Client:** those who pay for the roads to be built and maintained, also includes an agent acting on behalf of the client. The client group would include local authorities, national government, and regulatory bodies who are responsible for specifications for highway works, who determine which materials may be used in road construction and the methods for testing them. The client group should be concerned about the surface and structural conditions of their roads.
2. **Consultant:** those engaged in research and development, and design, for the performance of road products (materials and pavement construction). Consultants include consulting engineers and research institutions, who may require assurance about the properties (e.g. mechanical) of the road materials.
3. **Supplier:** those who manufacture and supply road materials (primary, recycled and secondary products) to meet road performance requirements. Suppliers include aggregates suppliers, demolition companies, bitumen production organisations, hydraulic binder organisations and materials processing companies.

4. **Contractor:** those who use materials to build and maintain roads to meet specified performance requirements, e.g. construction companies.

3.3 Overview of Roads

Roads are an essential part of modern day life, since they provide a platform for freight haulage in addition to satisfying the diverse range of business, recreational and commuting needs. The proportion of total passenger and freight movement made by road gauges the importance of main road networks. The road network has enormous economic and social benefits, generates substantial employments and contributes to GDP. Most economies now rely heavily on road transport for passenger and freight movement. Road needs are usually justified on the basis that there will be improvements to regional economic and transport situations, and no severe undesirable environmental impacts.

Road transport grew rapidly after World War II, and, in response to rapid traffic growth and deteriorated road systems, countries expanded their road networks considerably, particularly during the 1960s and 1970s (AASHTO 2004, Heggie and Vickers 1998). There are ongoing needs to provide new arterial roads where ongoing regional development proposals incorporate new transport links or where, as in Eastern Europe, modern roads were not constructed as they were in other places in the three decades from 1960 (Carpenter 2001b). Places, such as South America, Asia and Africa, need arterial roads in order to advance their transport infrastructure. In developed parts of the world the dominant needs are maintenance of existing road infrastructure and modifications (e.g. road repairs, strengthening, widening, and realignment).

Funds for road construction and maintenance around the world are becoming increasingly limited due to government reforms and a wider distribution of total funds to other public assets (Mundy 2002). As a result, pavement design and performance must generally work within more restricted budgets and produce economic products that consider many variables.

The performance of road pavements is mainly affected by traffic loading and the environment (notably moisture and temperature variations). Stresses from traffic loading on pavement materials range from being subjected to high stresses at the surfacing layer to being subjected to low stresses much deeper in the structure.

In considering the potential for using primary, recycled, secondary and blended materials the better solutions are those that integrate engineering properties, environmental factors and economic feasibility (OECD 1997). As shown in Figure 3.1, trade-offs in the integration will need to be made together with an understanding of the wider aspects, such as social factors, risk and political factors. Ogwuda, et al. (2003) have proposed a similar concept within a materials technology-management framework (based on materials technology, supply, demand and management (strategic and project)); the concept proposes the use of management processes to achieve a balance between supply and demand through materials technology.

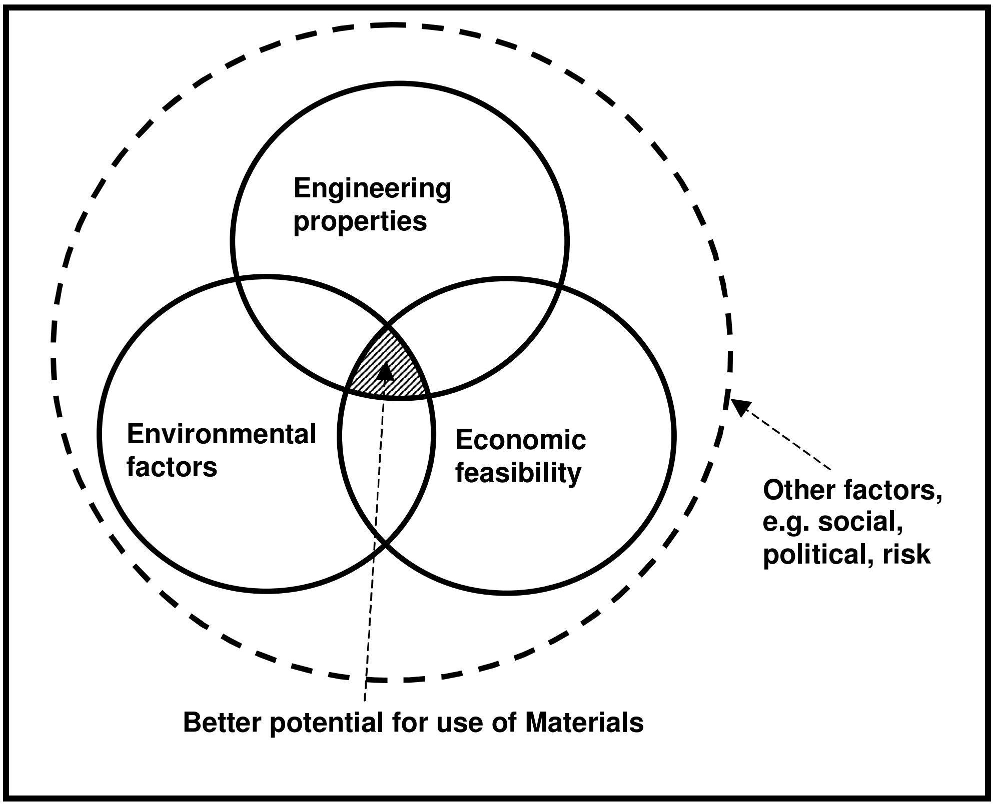


Figure 3.1: Potential for the use of primary and non-primary materials in road construction, adapted from OECD (1997)

The strong need for roads has been known right back to Roman days where the road network was developed to support travel and trade (around 300 BC). The Romans recognised that the fundamentals for good road construction were adequate drainage, good quality materials and workmanship (Lay 1998). Hence, it can be argued that performance requirements were in place as far back as when the Romans built their roads. To meet these performance requirements the early Roman roads generally consisted of four layers of materials overlying the soil, viz (Mundy 2002):

1. Stone slabs – surface course layer
2. Crushed stone – base layer
3. Stone blocks made of cement – sub-base layer
4. Sand layer – levelling layer.

A cross-section of an early Roman road is shown as Figure 3.2. These structures typically had retaining walls on either side to prevent slippage and were properly drained by a cambered surface with ditches running either side of the road to remove excess water (Lay 1998, Read 1996).

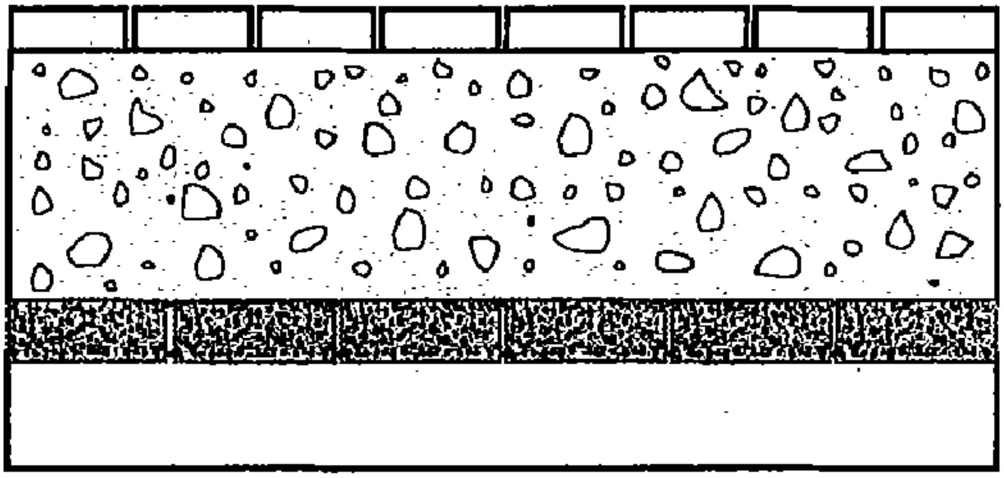


Figure 3.2: Cross-section of an early Roman pavement (Mundy 2002)

3.4 Road Pavement Structure

Road pavements are generally layered constructions that separate the tyres of vehicles from the subgrade (essentially soil), and thus protect the subgrade from the action of traffic and the environment (e.g. moisture and temperature).

Many factors affect the ability of road pavements to meet structural requirements. Mixture design, construction practices, properties of component materials, and the use of additives all play important roles in the resulting structural characteristics of a pavement. It is also important to recognize the interaction between mixture design and pavement design to arrive at the most cost-effective solutions. The wide range of cultural, geological and environmental factors in different countries has led to different emphasis in pavement construction (Dawson, et al. 2000).

Generally a road pavement has to provide two main functions:

1. Surface function, i.e. road user safety and comfort
2. Structural function, i.e. withstand traffic loading for the design period.

The functional layers in a road pavement are shown in Figure 3.3. Figure 3.4 shows the functional layer requirements and how the layers may be combined for a heavy-duty pavement.

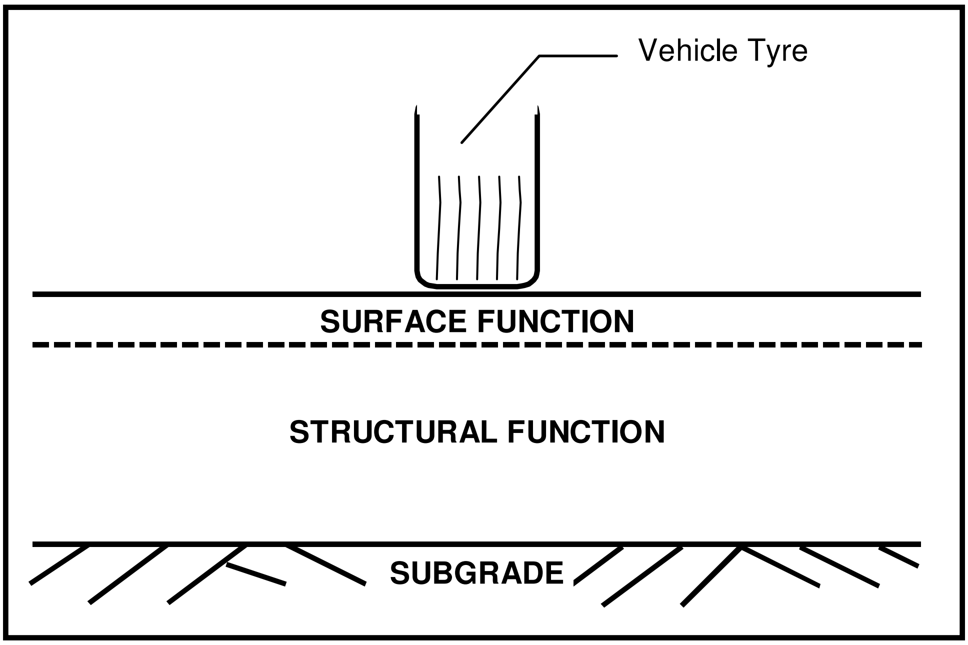


Figure 3.3: Functional layers in a road pavement

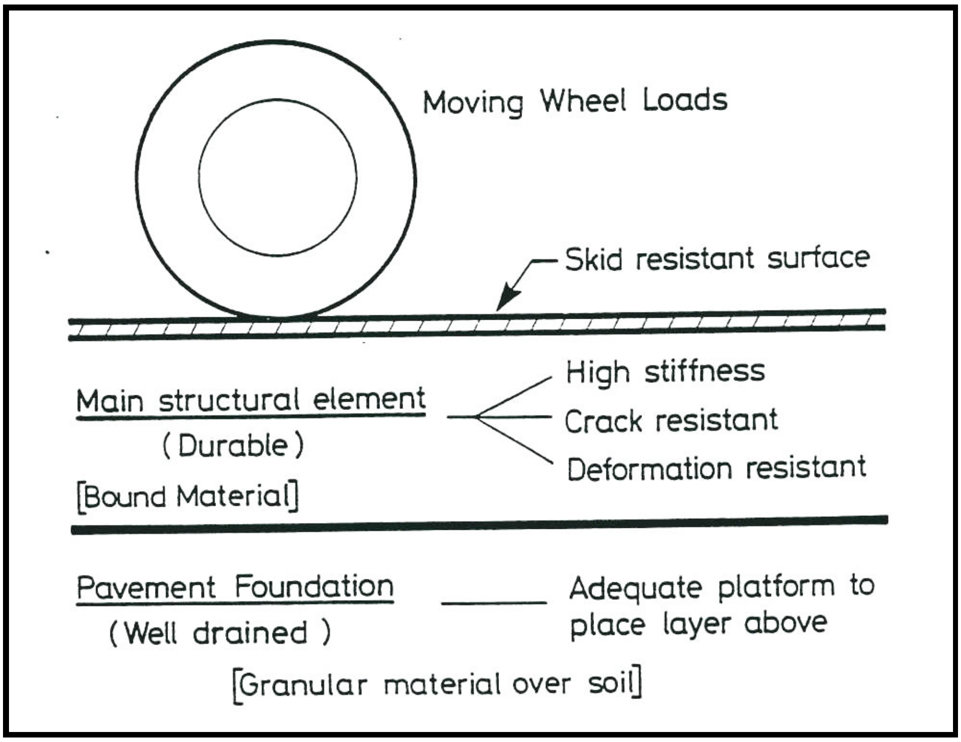


Figure 3.4: Basic functional requirements for heavy duty pavement layers (Brown 1998)

Typical pavement layer terminology associated with the functional layers in the road pavement is given in Figure 3.5. Road pavement layers generally form a staged stiffness/strength profile from high stiffness/strength, at surface level, to progressively lower stiffness/strength, at the top of the subgrade. The main functions of the surface course are to provide riding comfort, to provide safety and to provide adequate drainage (primarily to conduct water to the sides of the carriageway). In addition the surface course has to sustain stresses transmitted from the vehicle tyres. The underlying layers primarily distribute the stresses, transmitted from the surface course, in such a way that the subgrade is not overstressed.

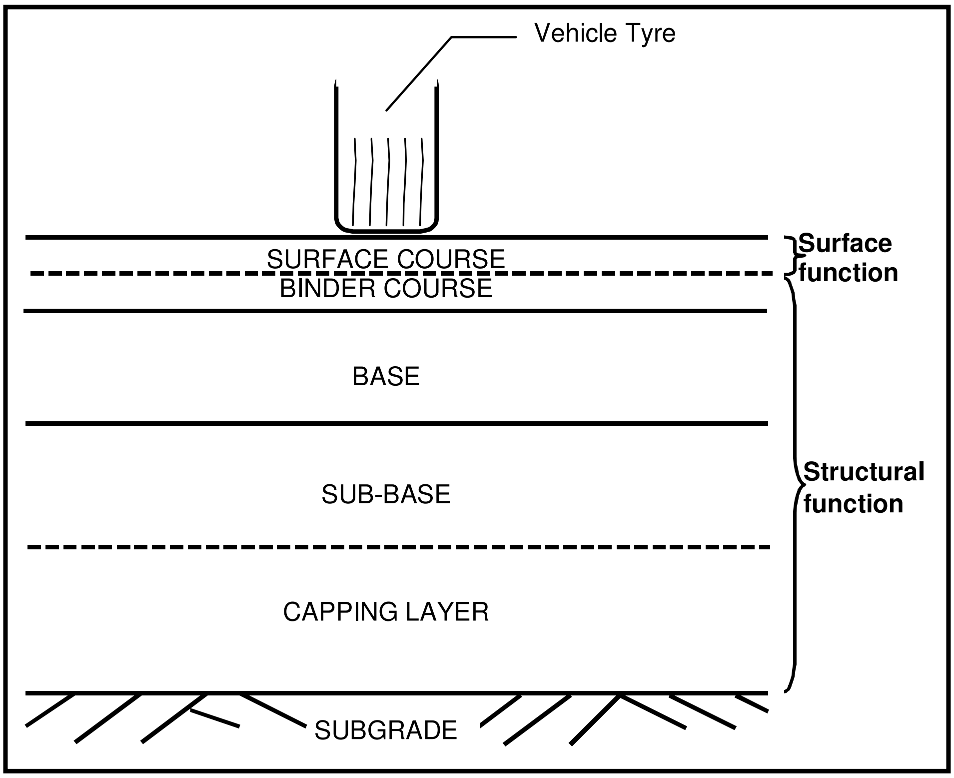


Figure 3.5: Terminology for functional layers in a road pavement

3.4.1 Road Pavement Structural Types

Layers in road pavements are typically asphalt bound, hydraulically bound mixtures (including concrete) and unbound (granular). The bound layers tend to be used higher up in the pavement, especially for heavily trafficked roads, while unbound layers are generally used lower down in the pavement structure. The layers could comprise primary, recycled, secondary and blended aggregates ranging in particle size from, nominally, less than 0.075 mm to 125 mm. Binders used in asphalt bound layers include straight-run bitumen, polymer modified bitumen, bitumen emulsion, foamed bitumen and cut-back bitumen. Binders used in hydraulically bound mixtures can be “lean” mixtures (with varying quantities of cement, slag or fly ash) or pavement quality concrete. Unbound granular materials are formed of compacted aggregate from geologic or industrial sources.

The main structural layers in flexible pavements (Figure 3.6) are asphalt-bound materials and the running surface is a specialised material chosen for its surface characteristics (e.g. skid resistance, low noise, (im)perviousness). Petroleum bitumen holds the aggregate particles together; but the aggregate is necessary to stabilise the road pavement. In the heat of day, bitumen expands in volume at up to ten times the rate of aggregates – hence it needs the aggregates to prevent bleeding at the surface and provide skid resistance. A useful way to provide stability is to select aggregates according to size, then mix them together to fit well and form a stable matrix.

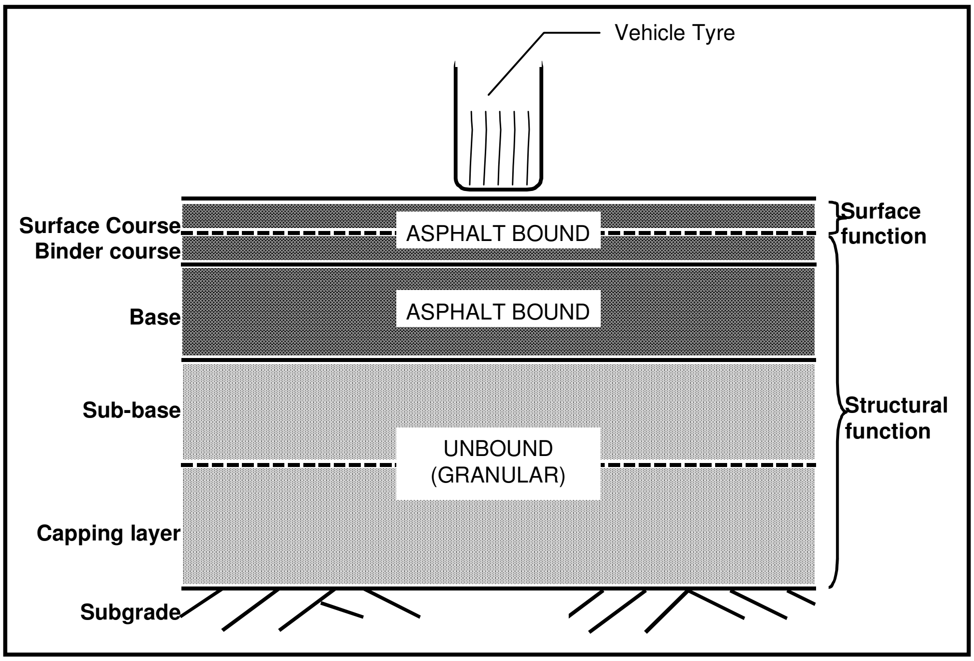


Figure 3.6: Possible cross-section of a flexible pavement

Rigid pavements (Figure 3.7) principally have the main structural layer as concrete, which may also serve as the running surface of the pavement.

Brown (1996a) gives other possible configurations of pavement constructions, which include gravel roads (commonly found in developing countries), composite pavements and block pavements.

Typically a well-designed and constructed flexible pavement may last 20 or 40 years, while rigid pavements may last 40 years or more if cracking is controlled. In many European countries only the top 80 to 100 mm of a road pavement are constructed of bound asphalt material. The remainder, which varies from 300 to 1500 mm in thickness, are constructed from unbound granular material; and pavements with thin surfacings and thicker unbound bases have been shown to be viable (European Commission - DGVII 1999).

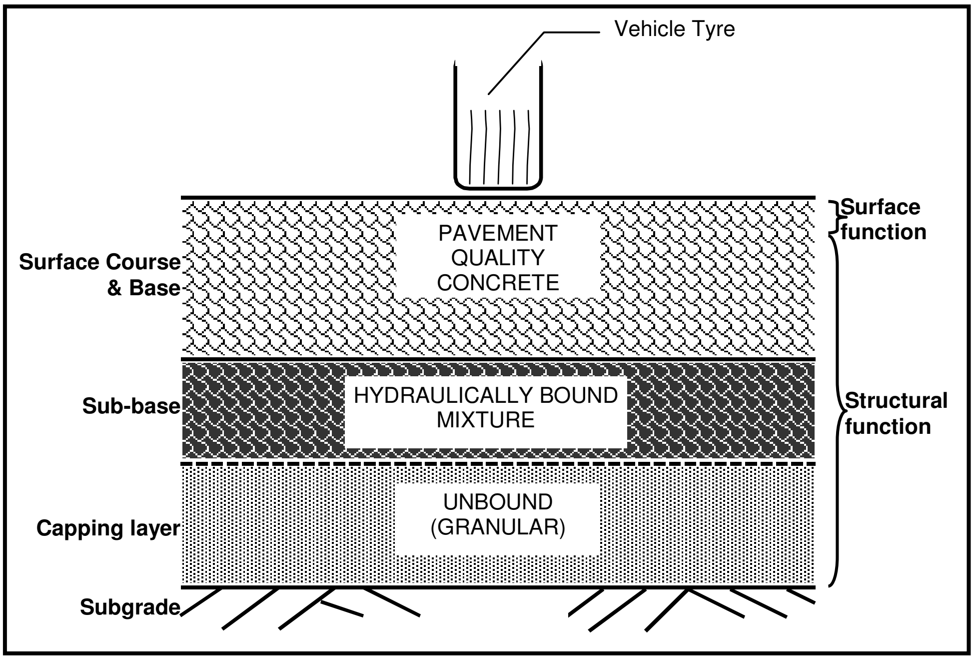


Figure 3.7: Possible cross-section of a rigid pavement

3.4.2 Wheel Loading on a Road Pavement Structure

When a pavement structure is loaded by a moving wheel load the stresses in any element in the pavement structure are functions of the distance between the rolling wheel and the depth of the element. There are (approximately sinusoidal) pulses of vertical and horizontal stress accompanied by a double pulse of shear stress with a sign reversal on the vertical and horizontal planes. During the passage of the wheel load over an element in the pavement system there is a stress change from shear loading to triaxial loading and subsequently back to shear loading (Figure 3.8). The duration of the stress pulse and magnitude of applied stresses would depend on the depth of the element in the pavement, and material type. In the lower layers of the pavement pulse times are generally longer and applied stresses generally lower than pulse times and applied stresses at the surface (Barksdale 1971). Elements in the lower part of an asphalt or concrete layer are tensile and compressive elsewhere (Brown 1996a, Paute, et al. 1996).

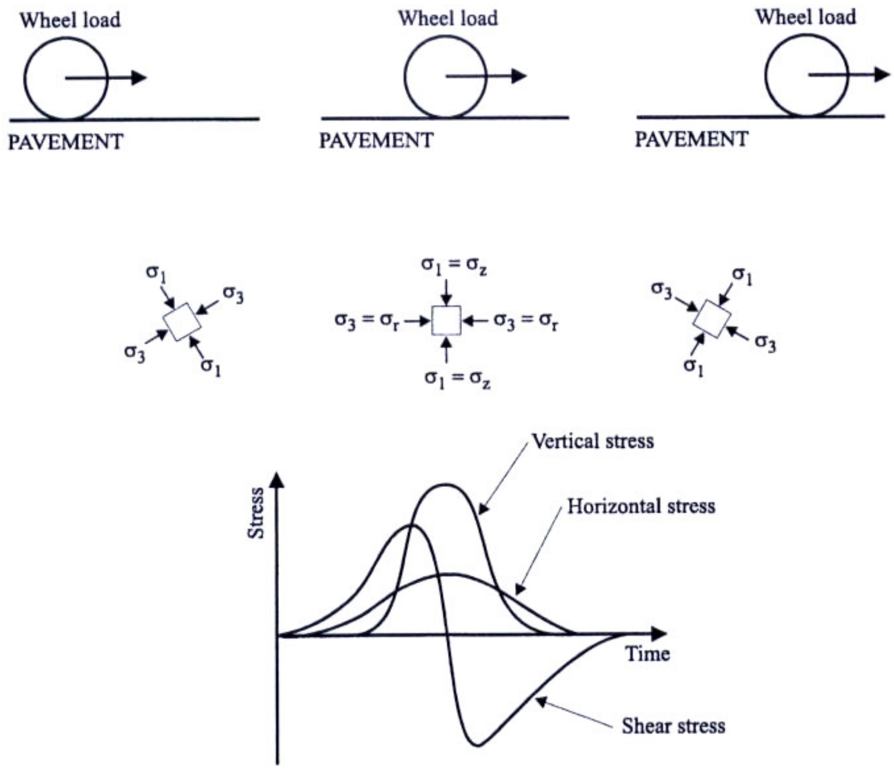


Figure 3.8: Stress conditions under a moving wheel load (Lekarp and Dawson 1998)

In comparing typical road pavement structures from different countries, current practice has been to use an equivalent axle loading system. This system allows for the composite effects of different axle types, which carry different magnitudes of loading to be converted to equivalent standard axles (ESA) for a given pavement type. The mass of a vehicle is converted to an equivalent number of standard (80 kN) axles using equation 3.1.

$$ESA = \left(\frac{w}{80}\right)^4 \qquad 3.1$$

Where:

ESA	=	Equivalent Standard Axle
w	=	Axle load (kN)
80	=	80 kN is the standard axle load (40 kN wheel load)

Equation 3.1 shows that the relationship between axle load and vehicle damage (ESA) is non-linear and that heavy axle weights do proportionally far more damage than lighter ones. For example, if the axle weight is doubled the

damage is increased sixteen times, i.e. one 160 kN axle loading is equivalent to 16 standard 80 kN axle loadings. It should be noted that the exponent of 4 used for calculating ESA will vary. Lower powers are usually associated with deteriorated pavements, e.g. initiation and progression of surface cracks, whilst higher powers are associated with stronger pavements, e.g. rigid pavements. Also, in European countries, the standard axle varies from 80 to 130 kN (European Commission - DGVII 2000, Hassan, et al. 2005).

3.5 Material properties

Material properties are an important aspect in the materials science appraisal for roadways. This section highlights some generic material properties that can be considered irrespective of materials source, i.e. primary, recycled or secondary.

3.5.1 Particle properties

Aggregate particle properties that influence the properties of unbound and bound mixtures are size, grading, shape (angularity), and texture (roughness). Maximum particle size, the fines content and the curve shape are important parameters. Curve shape can be characterised by the uniformity coefficient (C_u), given by equation 3.2 (Barnes 2000).

$$C_u = \frac{d_{60}}{d_{10}} \qquad 3.2$$

Where:

d_{60} = sieve through which 60% of the material passes

d_{10} = sieve through which 10% of the material passes

C_u values less than 5 are indicative of uniformly graded materials, while higher values of C_u are indicative of well-graded materials. However, C_u is not sensitive to “unstable” curves, i.e. curves with ‘sand bumps’. Hence, the curvature coefficient (C_c) is used and is defined by equation 3.3; C_c values in the range 1 to 3 are indicative of well graded aggregates (Barnes 2000).

$$C_c = \frac{d_{30}^2}{d_{10} \times d_{60}} \qquad 3.3$$

Where:

d_{30} = sieve through which 30% of the material passes

d_{10} and d_{60} are as defined for equation 3.2.

A well-known formula used to describe the curve shape is Fuller's equation, shown as equation 3.4 (Fuller 1905).

$$P = 100 \times \left(\frac{d}{D}\right)^n \qquad 3.4$$

Where:

P = percentage passing a particular sieve size (d)

D = largest sieve size

n = grading exponent, the shape of the curve (0 < n < 1)

A range of Fuller grading curves is shown as Figure 3.9, which shows the variation in fines content as a function of the grading exponent (n). The higher the grading exponent the coarser the grading (and less fines), and vice-versa.

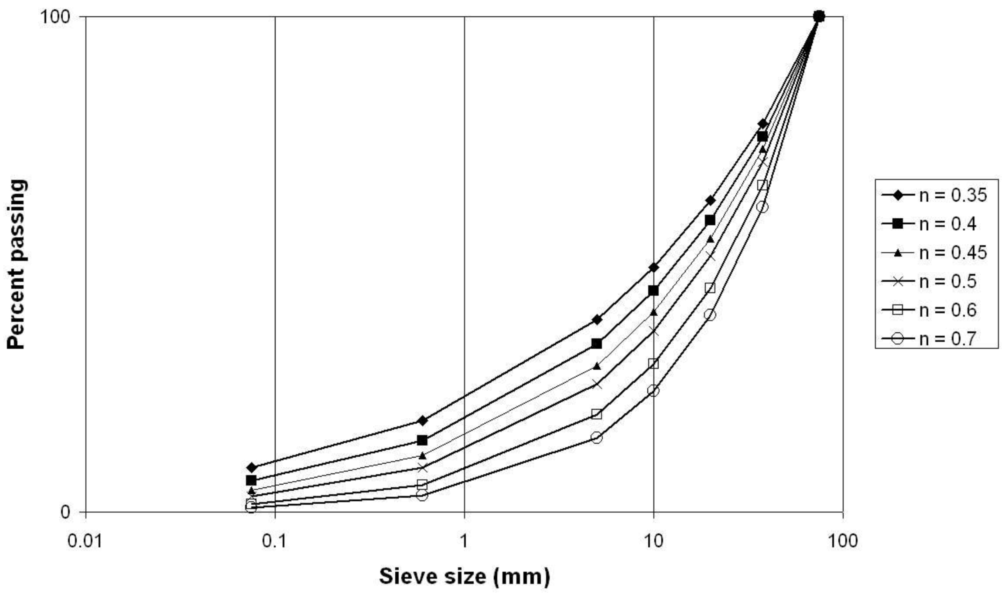


Figure 3.9: Some Fuller grading curves

The size of the aggregate particles that form the material skeleton that transmits the load is important for the stiffness, larger particles tend to give greater stiffness. It is also well known that the less steep the grading curve, the more stable the material (more well-graded or dense-graded material). To obtain the maximum number of contact points between particles (i.e. reasonable compaction), the distribution curve should have n values of 0.35 to 0.45 in equation 3.4 (Arm 2003, Cooper 1994). Aggregate grading controls the matrix void structure. Bituminous mixes with low aggregate voids are sensitive to small variations in bitumen content (Ahlrich 1995). If fines are excessive the mixture may lack stability and retain excess moisture. Conversely, if the content of the fines is low the mixture will tend to be stony and porous, and usually require additional fines to obtain good stability. However, it should be noted that the grading of a material is a balance between a dense one for high stiffness and strength and a more open-graded one for good permeability and hence drainage – which, in the case of unbound granular materials, allows for dissipation of pore pressures generated by traffic and reduced frost susceptibility.

The typical particle shape can be rounded or be angular. Angular material requires greater compaction, which could create crushing and an increase in fines. Conversely, a material with rounded particles is generally easier to compact but is usually more unstable than angular material. The shape and texture of coarse and fine aggregate control the strength, stiffness and rut resistance of unbound and bound mixtures thus affecting performance and serviceability. Rough angular aggregates produce higher quality pavements than smooth uncrushed aggregates. Flaky particles (defined as the ratio of thickness to width), either randomly orientated or not orientated parallel to the shear failure plane, increases the shear strength of the material. However, flaky particles do have problems with breakage, larger permanent strain under repeated loading and lower resilient modulus. Rutting from wheel tracking of flaky particles can be almost twice that of non-flaky material, and has been attributed to the alignment of the particles (Mundy 2002).

A loosely compacted material will deform under load as its constituent particles adopt a more closely packed arrangement and as air (and possibly water) is expelled. This results in a much stiffer response and the layer of material will suffer much less permanent and elastic deformation under subsequent traffic, and hence have a longer service life (Lay 1998).

Compaction, within reason, raises the shear strength of the material by increasing particle interlock and decreases permeability by decreasing available air voids. If a particle mass is subjected to a fixed compactive effort over a range of moisture contents the density varies depending on the moisture content, and the nature of the granular material. For most granular materials the variations can be explained as follows. When the moisture content is low the particle mass is stiff and difficult to compress thus low dry densities (high air voids) are obtained. As the moisture content increases the water acts as a lubricant thereby making the stiff mass more workable and hence particles become more closely packed. There is a reduction in the amount of air voids resulting in higher dry density. As the moisture content is increased the water nearly fills up all the air voids (i.e. close to 0% saturation) and pore water pressure develops and this keeps the solid particles apart which results in a decrease in density. Free moisture content (i.e. the fraction of moisture content, excluding water absorption) plays an active part in the compaction process.

3.5.2 Stiffness

The elastic stiffness is a measure of the ability of a pavement material to spread the traffic loading over an area of the pavement. With flexible pavements, the higher the elastic stiffness of the pavement and, hence, the individual layers the wider the area which reduces the level of strain experienced lower down in the pavement structure; with asphalt layers this effect is dependent upon both the temperature and speed of loading. Asphalt-bound materials have a greater load-spreading ability than unbound materials.

Stiffness is a measure of resistance to resilient deformation. It is expressed in terms of a modulus of elasticity or resilience that is used in designing a pavement. Resilient modulus is defined as the ratio of the dynamic stress to the recoverable (reversible) strain, measured as a result of the applied stress.

3.5.3 Fatigue

Road pavement failure by cracking under repeated wheel loading is a fatigue phenomenon. Fatigue cracking of asphalt pavements consists of two phases – crack initiation and crack propagation and may also be caused by temperature variation and construction practices (Read 1996). Crack initiation is generally described as the coalescence of micro-cracks to form a macro-crack under the repeated action of tensile strains, although it has also been suggested that the formation of the micro-crack is the crack initiation. Crack propagation is the growth of the macro-crack through the material under further applications of tensile strains; it has also been otherwise suggested that the propagation, densification and coalescence of micro-cracks to form macro-cracks is the crack propagation phase (Epps, et al. 2000, Read 1996).

Following crack initiation the road pavement is still able to sustain traffic loading, it is the extent of crack propagation that would indicate the extent of weakening of the pavement structure. Once a crack has been initiated the rate of propagation would depend on the tensile stress at the crack tip. The actual contact stress distribution under vehicle tyres plays a major role in the location and development of fatigue cracks. In addition, healing effect in bituminous mixtures and interfacial properties between asphalt and aggregate affect the rate of crack propagation (Read 1996).

In pavements with thinner asphalt layers cracking occurs from the top from outside the loaded area (Brown 1962). In thicker asphalt layers the cracking occurs within the loaded area but maybe initiated from the top or from the bottom depending on the thickness of the asphalt layer (Epps, et al. 2000). The thicker the asphalt layer the more likely it is that cracking will start from the top of the asphalt layer – this forms the basis of design for long-life road pavements for trunk roads in the UK (The Highways Agency (England), et al. 2001a).

Cracking may also occur from thermal cracking and reflection cracking; some description of these other forms of cracking for asphalt pavements are reported by Epps, et al. (2000).

3.5.4 Rutting

Rutting arises from the accumulation of vertical permanent strains in the wheel track, which can include contributions from all layers in the road pavement. Rutting (loss of stability) usually occurs in the top 75 to 100 mm of asphalt pavements, is characteristic of bituminous mixtures, hence these mixtures are typically designed for stability – if for no other distress mechanism (Ahlrich 1995, Epps, et al. 2000). In thick asphalt layers rutting can occur from permanent deformations in the asphalt layers only. Rutting in pavement layers occurs as a result of two processes (Ahlrich 1995, Collop 1994):

1. Densification – a consolidation or depression of pavement layers beneath tyre loads. This type of permanent deformation is caused by poor compaction during the construction of the layers or an inadequate mix design.
2. Plastic flow – a consolidation or depression in the pavement layers accompanied by upheaval on either side of the depression. Bituminous mixtures that exhibit plastic flow are generally caused by an unstable tender mixture.

In pavements with thin asphalt layers the unbound layers and subgrade may have a significant contribution to rutting, particularly if drainage conditions are unsatisfactory (Brown 1996a). There may also be concerns with rutting regarding construction traffic operating directly over the unbound foundation layers and subgrade. Hence, current UK design specifications are based on designs to limit rutting using the wheel tracking rate and depth (British Standards Institution 1998a, The Highways Agency (England), et al. 2001b, 2001c, 2005).

Stability is a measure of the ability to resist permanent deformation, i.e. load-bearing capacity, which could be defined as the load a layer of material can carry without being deformed more than the permissible amount. For deformation properties to remain the same over the life of the road the particle size and particle shape must not change, i.e. the material must be resistant to both mechanical and environmental effects. Road materials are exposed to mechanical action all the time they are handled from loading, unloading, spreading, compaction and traffic (construction and normal).

3.5.5 Material Behaviour Related to Water Content

One factor that is crucial to deformation properties, especially for fine-grained soils, is the water content (Arm 2003). In general, deformation in fine-grained soils exposed to repeated load increases with the increase in water content. This is due to low permeability in combination with the load that produces excess pore water pressure and subsequently decreases the effective stresses transmitted through the particle skeleton.

Several mechanisms can be responsible for damage resulting from the ingress of moisture into the pavement. In saturated materials, all the voids are filled with water. Since both the material and water are virtually incompressible, application of compressive stress to a saturated soil in poorly drained conditions will lead to a substantial build up of pore water pressure, which in turn will lead to a reduction in material strength and stiffness.

In unsaturated unbound materials, negative pore water pressure or suction contributes to the strength and the stiffness of the material. Suction may reach very high levels in unbound granular materials, leading to a large increase in material strength and stiffness. Even where no clay is present suction may still significantly influence material behaviour (Sweere 1990).

Although pavement engineers aim at keeping granular bases unsaturated, there are no guarantees that unsaturated conditions will prevail as water may enter the granular base of the pavement structure from below through capillary action or from above through cracks in the pavement layers. Unbound granular layers in road construction will generally be partly saturated for most of the year, with limited periods of full saturation.

One of the most important mechanisms by which asphalt pavements are damaged from water ingress is by stripping, in which separation of bitumen binder film from aggregates surfaces occurs as a result of prolonged contact with moisture and/or moisture vapour – the potential for stripping is related primarily to the aggregate type, binder grade, binder content, and air voids content. It is unlikely that bitumen will displace water on the surface of an aggregate and adhere to the aggregate. However, it is possible for water to displace the bitumen coating the aggregate. The more difficult it is for water to displace the bitumen, the less sensitive the mix is to stripping.

Recently, another form of moisture damage has been noted in the UK, when water enters the pavement and can become trapped between two layers of asphalt. The asphalt can fail as a consequence of traffic loading creating high hydraulic pressure gradients and movements of the trapped water. This in turn can cause it to physically scour the bitumen from the aggregate. Under these conditions the action can be so aggressive that all the asphalt will probably fail rapidly; a typical manifestation of this phenomenon is a pothole. To avoid these problems, water should be prevented from penetrating the road surfacing, and if it does the underlying layers should not be susceptible to moisture damage. The area of the road that is most susceptible to trapped water is in the layer interfaces and longitudinal construction joints (Sanders and Nunn 2005).

In order to measure the movement of water into, through and out of road pavements, it is necessary to know the relationship between water content and suction, and the relation of both to the hydraulic conductivity (Reid, et al. 2001).

To summarise, the action of water and water vapour may cause moisture damage including a reduction in unbound and bound bituminous mixture stiffness and strength, stripping of the binder from the aggregate, and further ageing of the binder resulting from exposure of new binder film surfaces to air. In-situ monitoring shows that the moisture in the pavement structure is very dependent on (European Commission - DGVII 1999):

1. Precipitation levels
2. Integrity of the sealed surface
3. Final preparation applied to the shoulders of the pavement (sealed or unsealed and seal width, partial or full)
4. Level of the pavement (raised pavement or pavement in cutting)
5. Ability of the pavement to self drain (the permeability of unbound granular materials and the adequacy of the pavement's drainage system).

3.5.6 Road Pavement Reinforcement

The reinforcement of pavement construction materials is effected by a reduction in the tensile strains that would otherwise develop at critical positions in the pavement (Brown 1996b). The apparent benefits of pavement reinforcement (i.e. when compared to unreinforced pavements) include reduction in pavement layer thicknesses, extension of pavement life and control of the onset and propagation of pavement cracks. Reinforcement is also used to overcome problems where a standard unreinforced solution cannot be adopted because of other constraints such as available construction depth, adjacent structures, and existing road furniture (Cooke 2006).

In concrete layers the reinforcement is generally in the form of steel bars while for asphalt bound, and unbound, layers geosynthetics are generally used. Geosynthetics is the collective term applied to thin, flexible, sheets of material (usually a polymer grid or geotextile) used in reinforcing soil, earthworks and pavements (Ingold 1994). Other materials used in pavement reinforcement include steel grids, glass grids and three-dimensional cellular polymer reinforcements.

3.6 Materials Technology Development

The technology of materials for use in various layers of the road pavement has been researched, developed and implemented over many years, which date back to the period of Telford and Macadam in the early 1800s. Potential applications have been tested in the laboratory and in-situ, under live or simulated traffic conditions. Recent years have seen considerable change with many new materials being developed as a result. The practice of (and research in) pavement engineering has seen significant developments from entirely empirically-based approaches, in the mid-1970s to more fundamental engineering procedures (Brown 1998, European Commission - DGVII 1999, 2000, Powell, et al. 1984, Shell International 1978, 1985, 1998).

For new products and technologies a typical sequence of events for materials development is as follows (adapted from Atkinson (1997), and OECD (1997)):

1. The identification of new product and/or technique.
2. Conducting systematic investigations and technical literature searches for previous applications of the product and/or technique or similar product/technique. Analysis of performance evaluations of previous research.
3. Laboratory and initial field trials. It is important that experimental work is representative of actual production, especially where there is the potential for the material to have variable quality.
4. Engaging the help of the client owner (e.g. local authority) to carry out limited scale site trials under the full action of real traffic, using normal operatives and plants, and monitoring the results.
5. Full-scale use of the product, again with a recording of the method and performance.
6. Initiating technical, economic, and environmental studies to identify most promising application of material.

7. Publishing of research results and conclusions. Provision of a precise description of the product/technique and technical data on its typical characteristics and variations. Characteristics should be representative of technical and environmental parameters.

8. Development of standards and specifications – technical community can use the research results to assist in development of national or international standards and specifications.

9. Establishment of quality control programme to monitor characteristics, variations, and performance of the product and/or technique on a continuous basis - this stage should involve all relevant stakeholders. This programme can be used for improvement of materials and techniques.

The technology has focussed on the need to reduce the noise of tyre impact, provide better skid resistance, reduce material costs and improve road pavement performance (Carpenter 2001b). In situations where traffic levels are occasional or very low (such as rural areas) unbound granular surfacing may suffice. However, as traffic levels increase it becomes more economic to seal these roads with a surface dressing or thicker (asphalt) layers. Sections 3.6.1 (Unbound Granular Materials), 3.6.2 (Asphalt Materials) and 3.6.3 (Hydraulically Bound Materials) describe the current broad categories for roadway materials how the materials technology has developed over many years.

3.6.1 Unbound Granular Materials

The amount by which unbound granular materials are deformed when loaded depends on stiffness and stability. Properties of these materials are dependent on compaction, which is in turn dependent on particle size distribution and particle shape. The mineralogical compositions, the internal structure of the particles, and the quality of fines (type of minerals) also have a considerable impact on deformation properties (Arm 2003). Mundy (2002) identified key material performance indicators (MPIs) which directly influence unbound granular material, and consequently pavement behaviour, as resilient modulus, permanent deformation (strain rate), durability, permeability, cohesion and angle of shearing resistance (Figure 3.10). Mundy (2002) further stated that these MPIs should be established in relation to a material's predicted state conditions (e.g. density, moisture content, grading) under the imposed traffic loading regime and influence of climate conditions.

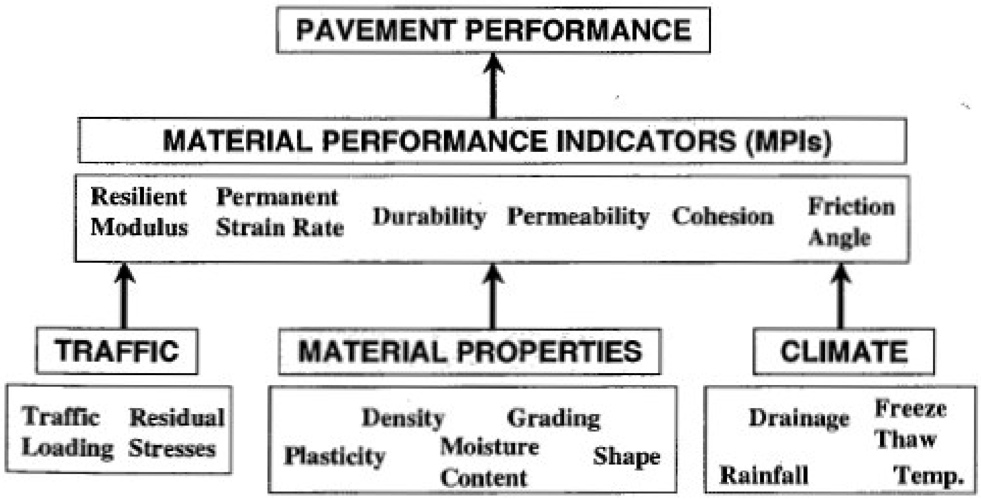


Figure 3.10: Components which affect pavement performance in unbound granular materials (Mundy 2002)

More fundamental research, and subsequently scientific understanding of granular material behaviour, has been ongoing since the mid-1970s and the results have led to more scientific practical applications that are economic, reliable and not necessarily over-designed (Correia 1996, Dawson, et al. 2000). Brown (1996a) identified the essential differences between soil mechanics requirements for pavement engineering and other geotechnical applications:

1. Soil below pavements and granular materials in pavements exist above the water table but beneath a sealed surface, although this does not completely inhibit the ingress of water. Hence, both saturated and partially saturated conditions can occur.

2. Soils and granular materials in completed pavements are subjected to large numbers of load applications at stress levels well below their shear strength.

3. Under partially completed pavements, when construction traffic is applied directly to the granular layer, the number of loads is fewer but the stress levels are much higher.

4. Under a single application of a moving wheel load, a pavement responds in an essentially resilient manner. However, irrecoverable plastic and viscous strains can accumulate under repeated loading. This presents the

opportunity to separate the theoretical analysis of pavements into two parts rather than to apply single elasto-plastic (or elasto-visco-plastic) analysis as is common for monotonic problems in geotechnics.

Unbound granular materials (including the subgrade) are now receiving the same level of research attention as asphalt and concrete pavement materials (Dawson 2000). In the past this had not been the case because much of the research was focussed on heavy duty pavements and their problems, generally associated with asphalt and concrete layers (Brown 1996a, Mundy 2002). The need to understand practice in different countries of Europe and to develop a more harmonised approach has led to more research in the mechanical behaviour of unbound granular materials in road pavements. Some research in Europe has also addressed the hydraulic properties of unbound granular materials in road pavements, from which client standards have been produced (British Standards Institution 2002, The Highways Agency (England), et al. 1990).

3.6.2 Asphalt Materials

For asphalt pavement construction new materials include proprietary thin surfacings, porous asphalt, stone mastic asphalt and cold mixes. Many materials have been developed, and are too numerous to describe in this thesis. Details of these mixes have been covered in various literature and Nicholls (1998) and Read (2003) give a useful summary.

Layer bonding and reflection cracking have been researched in road pavement technology and are covered in the literature (Collop, et al. 2003, Khweir and Fordyce 2003, Kruntcheva, et al. 2005, Nunn and Potter 1993, Sanders and Nunn 2005, Tarr, et al. 1999, Tschegg, et al. 1995). Layer bonding between asphalt layers is increasingly important because the degree of layer bonding can have a large effect on the bearing capacity of the pavement. If layers are not bonded, relative movement between the layers is possible and the horizontal strains will not be fully transmitted across the interface. Reflection cracking is a manifestation of cracks at the surface of asphalt layers that mirror those in the lower pavement layer, and is attributed to the increase in tensile stress within the overlaying layer resulting from traffic loading, cement treated bases, temperature variations, and moisture variations (Caltabiano 1990).

3.6.3 Hydraulically Bound Materials

The principal materials used for hydraulically bound stabilisation and modification of road pavement materials are lime, fly ash (pulverised fuel ash, PFA), and cement. While lime and cement are manufactured products, PFA is a by-product of the burning of coal at electric power generating stations. Hence, PFA generally exhibits greater variability than is seen in the other products (Little, et al. 2000). Other by-products such as kiln dust and fluidized bed ash from various manufacturing and energy generating processes are used to a lesser extent.

Improvements to the characteristics of marginal soils using small quantities of quicklime or hydrated lime have been used successfully worldwide. Lime stabilisation is a widely used means of chemically transforming unstable soils into structurally sound construction foundations. Lime stabilisation is particularly important in road pavements for modifying subgrade soils, sub-base materials, and base materials (e.g. clay-contaminated aggregate bases). The improved engineering characteristics of lime-treated materials provide important benefits to both rigid and flexible pavements. Lime stabilisation creates a number of important engineering properties in soils, including improved strength; improved resistance to fracture, fatigue, and permanent deformation; improved resilient properties; and resistance to the damaging effects of moisture. The most substantial improvements in these properties are seen in moderately to highly plastic soils, such as heavy clays.

Lime stabilisation involves adding lime, either quicklime or hydrated lime, to a suitable material (generally a clay soil with a PI (plasticity index) and clay content greater than 10%) (Holt and Freer-Hewish 1998). Typically, quicklime produces a more aggressive reaction compared to hydrated lime and changes the properties of the material (e.g. drying-out excessively wet materials through exothermic reaction) are consequently more rapid during the early reaction stage. Two reaction phases occur which are significantly different. Firstly, modification of the soil occurs resulting in a more workable material. Secondly, cementitious materials begin to form, which bond the clay particles together and improve the strength and durability of the host material. More information on the mechanism and chemical reactions that take place which result, firstly, in short-term soil modification and, secondly, in the longer-term requirement of soil stabilisation has been summarised by Holt and Freer-Hewish (1998).

Cement stabilisation involves mixing cement and water, in the correct proportions, with a suitable material. The products from cement stabilisation yield an interlocking gel that enmeshes the stabilised material particles. Not all soils can be successfully stabilised with cement. Sandy soils are usually suitable whereas soft clay is likely to yield unsatisfactory results. The higher the silt/clay content the higher the particle surface area and, hence, a greater and additional chemical reaction between the hydrated cement and soil particles. When cement is used to stabilise a granular material the cementation process is similar to concrete except that the cement paste does not fill voids between the soil particles. Any type of cement may be used in soil stabilisation but ordinary Portland cement is normally used. Cement has been found to be effective in stabilising a wide variety of soils, granular materials, by-products (e.g. slag and PFA), recycled materials (e.g. pulverised asphalt pavements) and crushed concrete. These stabilised materials are used in the pavement base, sub-base, and subgrade construction (Little, et al. 2000, The Highways Agency (England), et al. 2001b).

Stabilisation of soils and road pavement bases with PFA is an increasingly popular option. PFA stabilisation is used to modify the engineering properties of locally available materials and produce a structurally sound construction base. Both self-cementing and non-self-cementing PFA can be used in stabilisation applications.

PFA produced from the combustion of bituminous, anthracite, and some lignite coals is pozzolanic but not self-cementing. To produce cementitious products, an activator such as cement or lime will need to be added. Non-self-cementing PFA can be used to produce a lime/PFA/aggregate base (Little, et al. 2000, The Highways Agency (England), et al. 2001b).

Sub-bituminous coals are burned to produce self-cementing PFA, because of the presence of lime in concentrations typically ranging from 20 to 30 percent. However, most of the lime in these PFA is complexly combined with pozzolans, and only a small percentage is “free” lime (Little, et al. 2000). This characteristic may impact the suitability of the material for stabilisation of plastic clay soils. Self-cementing PFA can be enhanced with activators such as cement or lime, particularly if the self-cementing PFA does not have enough free lime to develop the pozzolanic reaction potential fully.

Recent developments in concrete technology have led to the production of ‘high strength concrete’ compared to ‘normal strength concrete’. Nowadays, the refinement of the cement manufacture and composition, the use of cement replacement materials, the use of chemical admixtures, such as water reducing admixture, could significantly improve the packing capacity of the mixture, resulting in a dense, high strength concrete. Concrete pavement technology has advanced in the use of surfacing layers of exposed aggregate (whisper) concrete and continuously reinforced concrete pavements, for crack control (Carpenter 2001b, Hassan, et al. 2005).

Continuous longitudinal reinforcement has the benefit of holding the transverse cracks tightly closed to ensure high load transfer across the cracks and improve the structural integrity of the pavement. Thermal stresses within the continuously reinforced concrete pavement (CRCP) slab are relieved by transverse cracks, which are held tightly closed by the continuous longitudinal reinforcement to ensure good aggregate interlock. The aggregate interlock results in a high level of load transfer efficiency across the cracks, maintaining the structural performance of the pavement.

Aggregate for use in concrete is traditionally specified by a combination of physical and mechanical properties with the assumption that the higher the strength of the aggregates the higher the strength of the concrete. However, this concept is not always valid and can restrict the wider use of alternative aggregates in concrete. An example of this is that siliceous gravel aggregate usually exhibits superior strength properties and lower porosity than limestone aggregate. However, when incorporated in concrete, the limestone aggregate gives higher strength properties and improved performance compared to siliceous gravel (Hassan, et al. 2005). Therefore, the strength and performance properties of concrete are not limited to the strength properties of the aggregate, but rather a combination of surface texture, mineralogy, particle shape and optimisation of the concrete mixture.

Controlled cracking in hydraulically bound layers has been researched in road pavement technology, the aim being to minimize crack width, maximise load transfer (through aggregate interlock) and delay the onset of reflection cracking (Al Hakim and Jennison 1999, Shahid and Thom 1996).

3.7 Pavement Materials Testing

This section reviews testing methods for pavement materials in the laboratory and in-situ. The testing methods included here are by no means comprehensive, but is an attempt to reflect the commonly used equipment in the field of road pavement engineering. Test methods have been developed to enable better understanding of the materials science of pavement materials.

In the past test methods have been developed for primary materials and may not allow a fair comparison to be made between primary materials and non-primary materials. An example of this would be Pulverised Fuel Ash (PFA) that has a slower strength gain in comparison to ordinary Portland cement (OPC), but ultimately both PFA and OPC may attain the same strength. Hence, performance specifications based on 28 day strength will always select OPC in preference to PFA even though in the long term both materials could have the same strength. A step forward in addressing this issue has been a recent UK guide on the use and specification of cold recycled materials for maintenance of road pavements (Merrill, et al. 2004). The guide utilises 1-year material properties, which enables slow curing materials to be used in an equivalent manner to traditional materials. Effectively, the materials science is similar except that the materials attain the required performance at a different rate.

There has been a proliferation of equipment for testing unbound granular materials and the limitations of these and their interpretation should be understood; precision and accuracy have generally been poor and there is only limited correlation between the data obtained from different test methods (Dawson, et al. 2000).

There are several categories of bituminous mixture evaluation tests, including simple strength tests, tests to determine permanent deformation characteristics, and tests to determine fundamental properties. Many laboratory testing systems have been proposed to evaluate resistance to cracking and rutting of bituminous mixtures, but none has been generally accepted or even verified to work for the variety of aggregates, binders, mixture types, environments, and loading conditions encountered in the asphalt industry (Epps, et al. 2000).

In summary, each testing system has advantages and disadvantages in applicability, cost, and level of complexity. Research, testing, design, construction, monitoring/evaluation, and maintenance should be carried out to the highest level of quality and technical standards possible. This is especially true for recycled and construction materials, that may be more variable compared to primary materials. However it is possible to reduce the extent to which these materials are considered to be variable by classifying them into broad material categories. This broad conceptual approach in material classification is presented in Chapter 4.

Sweere (1990) has made distinctions between laboratory and in-situ tests. In laboratory tests, properties are determined of the investigated material, without influence of the material in the pavement layers above and below the investigated material. Hence, laboratory tests determine actual material parameters. In-situ tests on the other hand often determine the combined properties of the layer on which the test is performed, and all layers below that layer. A “structure parameter” is determined, rather than a material parameter; the structure parameter being a function of compactibility during construction in combination with material parameters. In laboratory tests, often target values for the mechanical property of the investigated material are determined. The in-situ test is a check on whether the target values are met in the pavement layer after construction.

It may be more difficult to obtain consistent results from field (in-situ) testing as the stress conditions are much less controllable, compared to laboratory testing, and the response is more liable to fluctuation due to environmental factors. However, material response is a function of the material science of the pavement material. A better understanding of material science will allow for a better understanding of material response under variable in-situ conditions.

In laboratory conditions, materials can be tested under standardised conditions. Hence the required number of in-situ tests to assess material performance is usually greater than the required number of tests in the laboratory.

3.7.1 Laboratory Testing

Laboratory testing of small elements of the actual road pavement raises questions as to how representative of field (full-scale) conditions (e.g. stress state, stress-strain relationship) are the test results and to what extent are the environmental conditions replicated. An appropriate approach to laboratory testing is to select equipment that reproduces the field situation (Figure 3.8).

Most testing of soils and unbound materials for road pavements involves simple test configurations. These test configurations include the cyclic load triaxial test (Brown 1996a, Dawson 2000, European Commission - DGVII 1999). The cyclic load triaxial test is a laboratory method that is being used increasingly, especially in the context of performance testing of unbound granular materials. It is based on the principle that the specimen material is subjected to a simulated traffic load and material deformation monitored. Cylindrical specimens are compacted and subjected to cyclic loads of different magnitudes, to represent the vertical traffic load. A uniformly (cyclic or static) distributed pressure is applied to the curved surface of the cylinder. This represents the horizontal compressive stress induced by the restraint that the remainder of the pavement structure applies to the horizontal expansion of the cylinder under the vertically applied load. Stiffness (load-spreading ability) at different stress states can be calculated from the resilient strain. Permanent deformation of the material at different loads can also be determined and used as a measure of material stability. A European standard (BS EN 13286, part 7) has been developed for evaluating unbound granular materials in cyclic triaxial loading (British Standards Institution 2004).

The static triaxial test is used to determine the shear resistance of unbound granular materials under stress conditions likely to be experienced by the material in-situ within the road pavement (Mundy 2002). The static peak (or failure) stress is determined for different confining stresses that cover a range expected within the granular material of the loaded pavement structure. The static triaxial test can be used to determine the Mohr-Coulomb failure envelope for the resulting Mohr’s circles, from which the materials cohesion and angle of shearing resistance can be determined.

Compaction is a densification process in which air is reduced from the particle mass and the particles are packed more closely together. The process is usually carried out by mechanical means such as static (dead-weight), vibratory, impact or kneading equipment. The effect of compaction is an improvement in material properties such as increased strength, reduced permeability, and reduced compressibility. The degree of compaction that can be achieved depends on compactive effort, density, grading, moisture content and percent air voids in the particle mass. The objective of the compaction test is to establish the relationship between the dry density and moisture content of the granular material, hence determine the maximum dry density (MDD) and optimum moisture content (OMC). Figure 3.11 illustrates the above relationship; and also shows the variation in CBR within the relationship. The percent air voids lines (generally 0% and 5%) can also be plotted giving an indication of the degree of saturation of the particle mass.

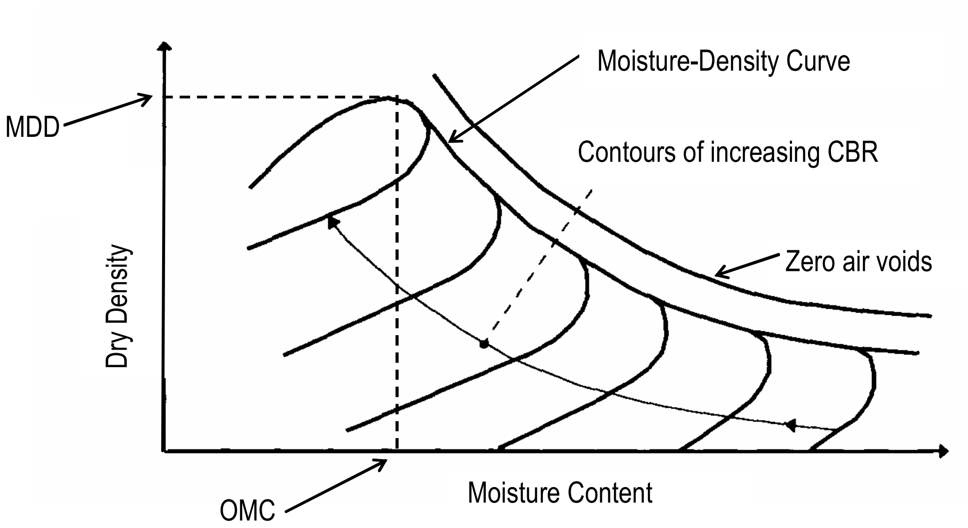


Figure 3.11: Relationship between Moisture Content, Dry Density and CBR

The effect of an increased compactive effort is to increase the magnitude of the MDD and reduce the magnitude of the OMC (a decreased compactive effort does the reverse). The effect of increasing the compactive effort at a given moisture content is to bring the particle mass closer to the saturation line (the moisture content at this stage may be higher than the OMC for the increased compactive effort).

Double peak densities separated by a point of low density, at pessimum moisture content, may also occur in the moisture-density curve (British Standards Institution 1980). The reason for the peak density at low moisture content is attributed to capillary forces resisting rearrangement of particles, friction between mass particles, and thin films of water increasing friction between sand particles (Lambe and Whitman 1979, Pike 1972, Taylor 2000). The dry side of the moisture-density curve maybe steep or flat. These differences are due to grading, with well-graded soils tending to produce a flatter dry leg curve (Lee, et al. 1983).

The test most widely used to determine moisture-density relations of soils and unbound granular materials in the laboratory is the Proctor test. The test initially involves compaction of soils in a 101.6 mm (4 inch) mould using a drop hammer to apply the compaction effort. Various versions of the test have since been developed and standardised using two levels of compaction (light and heavy compaction) and two mould sizes (diameters of approximately 100 mm (1 litre) and 150 mm (2 litres)) (British Standards Institution 1990e). The test is now used for soils, sands and unbound granular base materials. With the unbound granular materials, degradation of the material tested can occur, especially in the case of porous materials. Laboratory testing procedures may also be undertaken to determine optimum binder (e.g. cement, lime) and moisture content requirements; samples being cured under simulated field conditions.

The California Bearing Ratio (CBR) test was developed in the 1930s and attempts to quantify the response of the pavement foundation and subgrade to in-service loading. The test is used to estimate the bearing capacity of unbound granular materials in construction, and is generally used in the design of road pavements. The CBR test is a static load empirical test to failure and hence does not model repeated loading effects. In addition, the test is not a direct measure of stiffness or shear strength (The Highways Agency (England), et al. 2005).

The laboratory CBR test is a standard load–penetration type test that involves driving a plunger of standard dimensions into a cylindrical mould of the recompacted material at a standard rate and measuring the load required to cause penetrations at standard intervals. The sample can be inverted and the process of penetration repeated. Essential features of the test equipment are shown in Figure 3.12. The loads causing penetrations of 2.5 mm and 5.0 mm are compared with loads causing similar penetrations of a standard well-graded fine crushed limestone rock (first standardized in California); the CBR of the standard crushed rock is 100%. These sample loads are then expressed as a percentage of corresponding standard crushed rock loads to determine the CBR. Annular (surcharge) weights (not shown in Figure 3.12) can be used to simulate the effect of the overlying pavement layers on the CBR. The test can be performed at optimum or natural moisture content or under saturated conditions; but comparisons between materials will be undertaken for the same moisture content type. With coarser graded materials, and to avoid bias test results due to the size of the CBR plunger and mould, the removal of coarse particles is recommended (British Standards Institution 1990e).

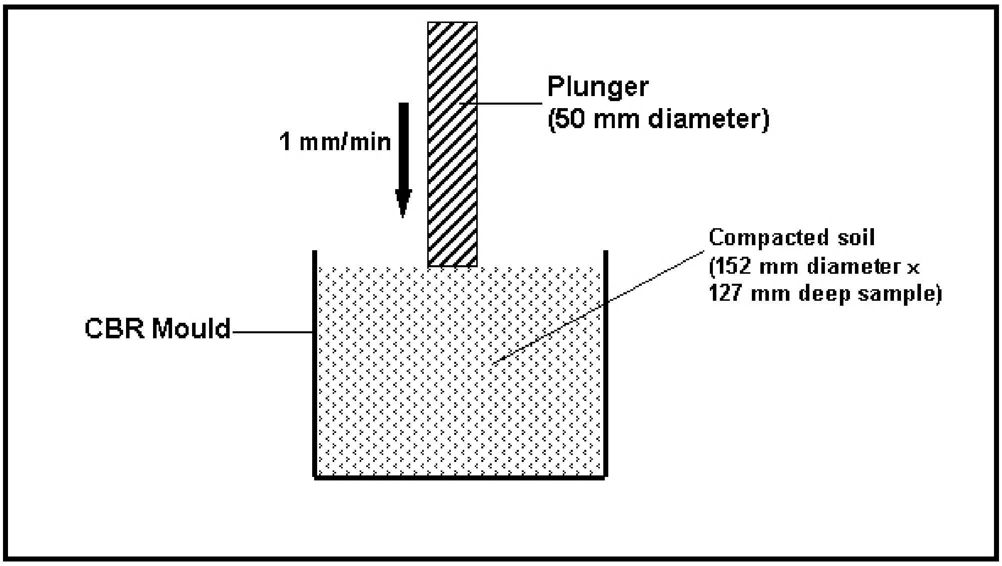


Figure 3.12: Laboratory CBR test

In-situ CBR tests are sometimes carried out but tend to give lower CBR values than laboratory CBR values due to the confining conditions of the laboratory mould. However, for cohesive soils close to saturation the laboratory CBR test will give lower values than the in-situ version of the test due to the development of positive pore pressures during the laboratory test (Croney 1977, Croney and Croney 1991). It has been reported that the test is essentially an index test for shear strength and the design principles were based on prevention of subgrade shear failure in pavements with thin surfacings (Brown 1996a). Due to the simplicity, cheapness and relative speed of the test it is still used widely.

Simple and uncompacted particle-based assessments of unbound granular materials such as the Los Angeles Abrasion test and micro-Deval tests are currently being used across Europe (European Commission - DGVII 1999).

The European Los Angeles test is a modification of the original test method from the 1920s. 5 kg of the 10 to 14 mm fraction of the material is subjected to 500 revolutions in a steel drum together with 11 steel balls. The micro-Deval test was originally developed in France in the 1960s. In this test, 0.5 kg of the 10 to 14 mm fraction of the material is subjected to 12,000 revolutions in a steel drum together with 5 kg of steel balls and 2.5 litres of water (British Standards Institution 1996, 1998b). Particle-based tests from the UK which do not form part of the new European standards are the Aggregate Impact Value (AIV), Ten percent Fines Value (TFV) and the Aggregate Crushing Value (ACV) (British Standards Institution 1990a, 1990b, 1990c).

It has to be questioned whether single-sized uncompacted particle-based assessments can truly evaluate mechanical behaviour of the whole aggregate mass used in road pavements. This is because heterogeneous materials such as demolition rubble may have a 10-14 mm fraction which is significantly different from the rest of the material. Also, tests do not simulate local environmental conditions experienced in the road pavement and this can bias the resulting performance assessment (Mundy 2002). Laboratory tests tend to underestimate field performance and this has been shown in cases involving recycled and secondary materials (Arm 2003, Dawson, et al. 2000, Reid, et al. 2001). Arm (2003) has stated that although recycled products often generate a significant amount of fine materials, the fines are not plastic as may be the case with primary materials. However, these simple tests are generally more suited to day-to-day use, e.g. quality control – hence there maybe a requirement to relate fundamental material properties to simple particle characteristics.

Bitumen specifications have seen dramatic changes from simplistic, empirical tests to fundamental, visco-elastic and damage characterization methods. The development of the specifications up until 1990 was based on simple concepts of hardness and viscosity. In many countries the specifications were dominated by two “simple” empirical tests, namely the Penetration and the Softening Point, related to in-service temperatures and the (Newtonian) viscosity related to mixing and compaction temperatures. These specifications are not directly related to performance, because they are based on experience and are only valid for penetration grade bitumen (Van De Ven, et al. 2004).

The Nottingham Asphalt Tester (NAT) is a flexible piece of equipment developed in the mid 1980s to provide an easy-to-operate device for determining the fundamental mechanical behaviour (e.g. stiffness, fatigue strength and resistance to permanent deformation) of asphalt materials (Brown, et al. 1994). It is now generally accepted worldwide as one of the basic tools for investigating the resilient and permanent strain responses of asphalt bound materials. The NAT test configurations (including cyclic loading) can be used for various test methods given in current European standards (British Standards Institution 2003-2005). It may also be used for soil and unbound granular specimens to determine stress-strain relationships.

3.7.2 Field and Full-Scale Testing

Field and full-scale testing have the potential of being relatively more useful than laboratory testing as the material is assessed at real levels of material qualities (e.g. compaction, grading). Employing the best equipment and methods, also has great potential in quality control and materials evaluation. However, for this to be of value the relationships to laboratory measures need to be elaborated, specifications for use need to be employed, and the best equipment and methods must be determined. Impact-type testing with modern electronic interpretation can be relatively rapid and economic and many repeat measurements over a wide area are possible without great difficulty.

A large number of full-scale experiments have been conducted to obtain an insight into the response of pavements to transient wheel loading. Full-scale experiments may be in the form of accelerated pavement testing (APT). APT may be defined as the controlled application of a prototype wheel loading, at or above the appropriate legal load limit to a prototype or actual, layered, structural pavement system to determine pavement response and performance under a controlled, accelerated, accumulation of damage in a compressed time period (Jenkins, et al. 2004). APT monitors pavement deterioration using accelerated loading devices at full-scale sizes. A summary of the these devices is given by Brown (1998, 2004).

One of the more notable APT was the AASHO (American Association of State Highway Officials) road test (Highway Research Board 1962). A number of pavements were tested by running various vehicles over various test tracks.

The results from the test have formed the basis for computation of vehicle damaging effect (equivalent standard axle) on the road pavement, which has been used extensively in pavement design.

Other APT include the Transport Research Laboratory (TRL) pavement testing facility and the heavy vehicle simulator (HVS) developed in South Africa. The TRL pavement test facility is an accelerated traffic loading test facility where the performance of full-scale pavement structures and materials can be assessed. The pavement test facility also allows a choice of dual or single wheel assemblies, canalised or laterally distributed wheel load, and pavement heating capabilities (Sanders and Nunn 2005). The HVS uses high wheel loads repeatedly and continuously (24 hours a day, 7 days a week) over several weeks to simulate many years traffic loading.

The Falling Weight Deflectometer (FWD) is an impact-type testing equipment and is used to assist with detailed structural evaluation of the road pavement. The testing system is usually trailer mounted and applies an impulse force by dropping masses from different heights onto a spring system that transmits the load to a steel plate. Deflection transducers located at set distances from the line of symmetry of the steel plate, and mounted on a bar that is automatically dropped with the loading plate, give the shape of the deflection bowl. The magnitude of deflection indicates the level of deterioration that has taken place in service and forms a basis for design of rehabilitation. High values can indicate the need for major reconstruction, whereas lower values allow the existing material to remain in the structure and be properly characterized for rehabilitation design purposes. The FWD is suitable for the evaluation of flexible and rigid pavements, and is able to quantify load transfer at joints in concrete pavements and to detect deterioration caused by shrinkage cracks in cement-treated layers before the appearance of reflection cracking at the surface Brown (1998, 2004).

Data collected from the FWD can be used in the estimation of the elastic modulus of the pavement layers. The moduli are estimated through back calculation and modelling the structure as a multilayer system. The back calculation procedure consists of calculating deflection values and comparing these with the measured deflections. Any differences are minimised by adjusting the layer stiffnesses.

Low-cost field instrumentation has also been developed for road pavements, and application of this instrumentation should provide clearer understanding about in-situ performance of road pavements.

The Dynamic Cone Penetrometer (DCP) comprises a cone that is driven into the foundation by repeated drops of a mass. The rate of penetration of the cone through a material is a measure of its strength, where the lower the penetration rate, the higher the strength of the material. Changes in penetration rate indicate boundaries between different layers, allowing layer thicknesses to be determined (Jones 2004).

The Clegg Impact Tester (CIT) was developed in the mid 1970s in Australia for density control of unbound base layers. The basic principle behind the CIT is to obtain a measurement of the maximum deceleration of a free falling cylindrical hammer (contained in a guide tube) from a height of 450 mm onto a surface under test (Zohrabi and Scott 2003). The original standard test protocol was to drop the hammer four consecutive times on the same location with the highest value result in the series taken as the Peak CIT result. Since that time, other test protocols have been used based on the materials under test and the application. These other protocols vary the hammer drop height or use the average result in place of the peak. The Clegg offers the convenience of rapidly scanning compaction variation over large areas, is cheap and portable. As the dimensions of the drop hammer are similar in dimensions to the CBR piston, the CIT can be regarded as a dynamic version of the CBR and correlations between CBR and CIT have been obtained (Garrick and Scholer 1985, Sweere 1990).

3.8 Pavement Stiffness Modelling

It is common to characterize pavement layer materials by their (resilient) stiffness, as defined in section 3.5.2, and Poisson's ratio, which is directly related to field performance (Ullidtz 1987). The development of stiffness theory in relation to road pavements (asphalt and unbound layers) is summarised by Brown (1996a). The use of stiffness provides a link between pavement analysis and design, which needs this parameter as an input, and testing (specifications) which allow (require) it to be quantified. Stiffness is required to determine load-induced and thermal stress and strain distribution in road pavements, which in turn is used to reflect the deterioration that has taken place in service and form a basis for design of rehabilitation, e.g. major or partial reconstruction or overlay design purposes (Brown 1998). In addition, the road surface has to provide satisfactory characteristics such as adequate skid resistance, acceptable noise levels, drainage and riding comfort.

Elastic modulus and Poisson's ratio as defined for most civil engineering materials can only be applied to pavement materials in the broadest sense since properties such as plasticity, dilatancy, viscosity, elasto-plasticity, visco-elasticity tend to complicate the relationship between stress and strain; the relationship is further affected by temperature, moisture content, time or frequency of loading, and stress state (Brown 1996a, Collop, et al. 1995, Epps, et al. 2000, Lay 1998, Lu, et al. 2002, Ullidtz 1987, Wolff and Visser 1994).

With the advent of pavement analysis, modelling and design empirical relationships between the CBR and stiffness became a necessity, and were established. Heukelom and Foster (1960) developed a relationship between stiffness and CBR for soils and granular materials from the displacement under the CBR plunger using Boussinesq's equation for the deflection under a circular uniform load on an elastic half space; and correlating this with experimental data for a wide range of materials arrived at the relationship shown as equation 3.5.

$$E = 11 \times CBR \tag{3.5}$$

Where:

E	=	Stiffness (MPa)
CBR	=	California Bearing Ratio (%)

Equation 3.5 has been generally rounded off to E = 10 × CBR, which was also used in the Shell pavement design manuals (Shell International 1978, 1985). Note that equation 3.5 does not generally apply to bound materials, i.e. asphalt and hydraulically bound materials.

The UK-based Transport Research Laboratory (TRL) developed another relationship between E and CBR. Their relationship was based on a comprehensive analysis of wave propagation data, supported by information from cyclic load triaxial testing and in-situ measurements of transient stress and strain in experimental pavements. The TRL relationship is shown as equation 3.6 (Powell, et al. 1984).

$$E = 17 \times CBR^{0.64} \quad 3.6$$

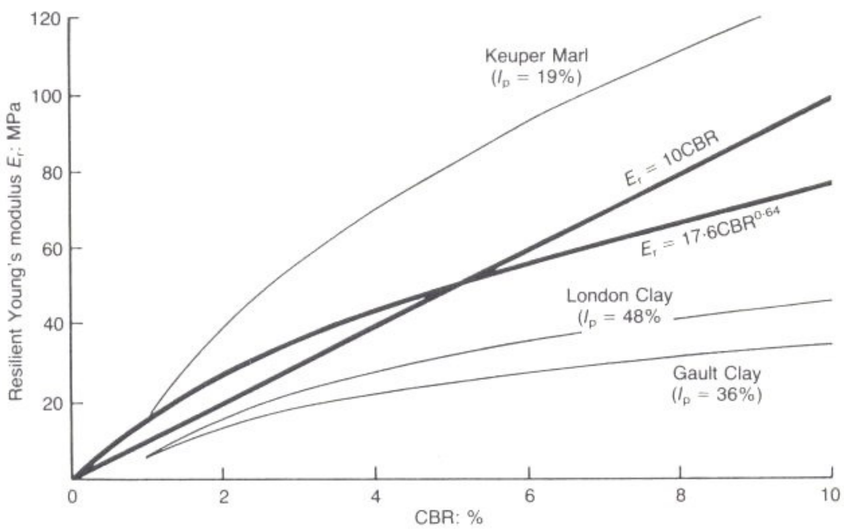
Where:

E = Stiffness (MPa)

CBR = California Bearing Ratio (%)

(Equation 3.6 valid for CBR in the range 2 to 12%).

Brown (1994) checked the validity of equations 3.5 (rounded-off) and 3.6 for three fine grained soils by performing both cyclic load triaxial tests and CBR tests in saturated and partially saturated specimens; hence yielding various stiffness and CBR values for the soils. Figure 3.13 shows the resilient stiffness (E_r) of the three soils at a stress pulse of 40 KPa plotted against CBR, together with the relationships given by equations 3.5 (rounded-off) and 3.6. From these results Brown (1994) concluded that the E-CBR relationships only gave a rough guide to expected soil stiffness (i.e. CBR not directly comparable to stiffness), although equation 3.6 (TRL relationship) is of the correct shape.



(I_P = plasticity index)

Figure 3.13: Relationship between stiffness and CBR for three types of soil at a stress pulse of 40 kPa (Brown 1994)

Due to stress dependency of soils and coarse graded granular materials, a concept (such as the E-CBR relationship) of a single stiffness for any unbound granular material that does not involve a stress factor is invalid. The CBR test is a combination of elastic (stiffness-related) and plastic (strength-related) deformation and the two may be difficult to distinguish from the CBR test; hence a purely elastic parameter, such as stiffness, may be difficult to determine from the CBR test. Sweere (1990) suggested that in order to characterise the stiffness of an unbound granular material with one single value the cyclic load triaxial testing at a stress level representative of field conditions should be used. Other relationships have been developed for characterising the subgrade and unbound granular materials – a useful summary of these relationships is given elsewhere (Karasahin, et al. 1993, Lekarp and Dawson 1998, Lekarp, et al. 2000a, 2000b, Sweere 1990).

Asphalt stiffness has been modelled on the stiffness of the bitumen, percent volume of bitumen and the volume of the aggregate. In 1977, Shell produced a nomograph (Figure 3.14) for predicting asphalt stiffness (Claessen, et al. 1977). The University of Nottingham also developed a relationship for calculating asphalt stiffness, reproduced, as equation 3.7 (Brown and Brunton 1992).

$$
\begin{aligned}
S_{me} &= S_b \left[1 + \frac{257.5 - 2.5\ VMA}{n\ (VMA\ - 3)} \right]^n \\
n &= 0.83\ \log\ \left(\frac{4 \times 10^4}{S_b} \right)
\end{aligned}
\qquad 3.7
$$

Where:

S_{me} = mix elastic stiffness (MPa)

S_b = bitumen stiffness in (MPa)

VMA is in percent (12 – 30%) (Brown and Brunton 1992).

The two asphalt stiffness determination procedures are valid for bitumen stiffness exceeding 5 MPa, i.e. under high stiffness conditions appropriate to moving traffic where the response is predominantly elastic. The two methods assume that the grading, type and characteristics of the aggregate affect only the elastic stiffness of the mixture since they influence the packing characteristics of the aggregate, and thus, the state of compaction of the material (Read and Whiteoak 2003).

3.9 Pavement Performance Modelling

Linear elastic analysis can be used with reasonable confidence for road pavements with thick asphalt or concrete layers for simplistic modelling of pavement structure, but is considered unsuitable for unsurfaced or thinly surfaced pavements unless the non-linearity of unbound layers can be modelled. For asphalt pavements with traffic moving under normal conditions, hence with a specified loading time, and a known temperature it is reasonable enough to assume linear elasticity. Road pavements in which the response is dominated by the resilient response of the granular materials and soil should take account of non-linearity of the material (Brown 1996a, European Commission - DGVII 1999).

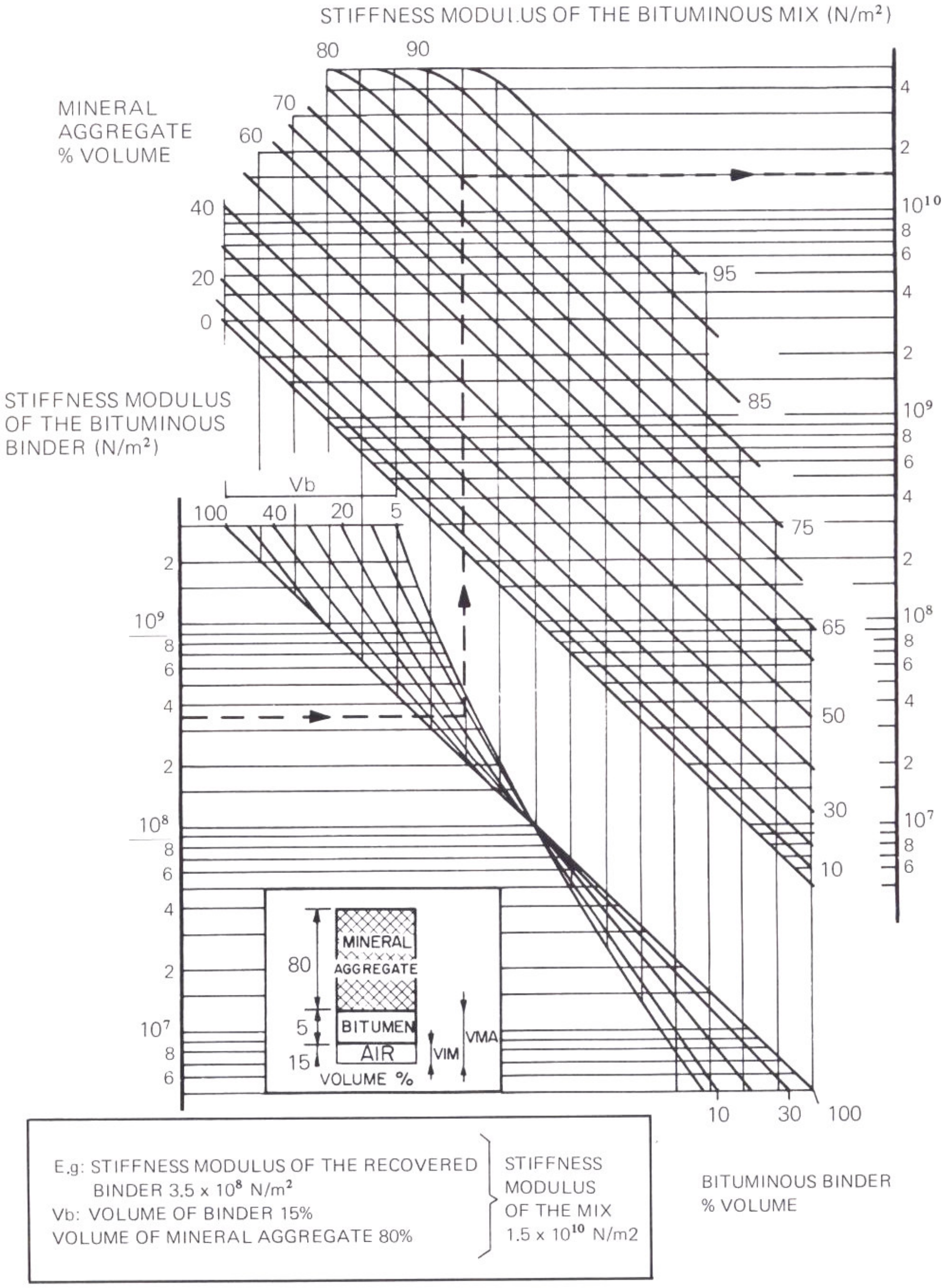


Figure 3.14: Nomograph for predicting the stiffness modulus of asphalts (Claessen, et al. 1977)

Collop (1994) carried out a review of models used to calculate fatigue damage from the primary responses (stresses, strains) in the asphalt layer for fatigue cracking from both the surface and the base of the bound layers. Two main models were identified. The first approach is to determine the fatigue life of the asphalt material from the maximum tensile strain (or stress) in the asphalt layer. This type of fatigue model has been developed from laboratory experiments and is typically a power-law relationship of the general form as shown in equation 3.8.

$$N_f = k_1 \varepsilon^{-k_2} \qquad 3.8$$

Where:

N_f	=	number of cycles to failure
ε	=	tensile strain
k_1, k_2	=	material constants

k_1 and k_2 are typically determined from simple laboratory fatigue tests on specimens of asphalt material. From equation 3.8, the fatigue life of asphalt is very sensitive to the exponent k_2. Experimental studies have shown that the major factors affecting the constants k_1 and k_2 are (Collop 1994):

1. bituminous mixture stiffness
2. bituminous binder content
3. bituminous binder type
4. viscosity
5. gradation and characteristics of the aggregate
6. air void content
7. pavement temperature

One of the problems with this type of model is the simplified loading conditions under which the fatigue constants k_1 and k_2 are determined, laboratory experiments tend to under predict the fatigue life due to the following reasons (Thom 1994).

1. Does not take into account “rest periods” and “healing”, in asphalt layers, between load applications in real traffic, even on heavily trafficked roads.
2. Lateral wander of wheels along the wheel track means that traffic loading in a wheel track is not applied in the same location each time.
3. Crack propagation needs time for propagation through the pavement layer, whereas in controlled stress fatigue tests there is no time for crack propagation.

As a result of the above, an increase in fatigue life ranging from 5 to 700 times the values obtained in the laboratory has been proposed (Collop 1994, Read 1996, Thom 1994). Fatigue models for concrete layers in road pavements often take the form of equation 3.8 (Lay 1998, Majidzadeh 1988).

The second approach to relate fatigue damage to the primary responses (stresses, strains) in the asphalt layer involves the use of linear elastic fracture mechanics. Typically, the stresses in the vicinity of a crack are calculated and then related semi-empirically to rate of crack growth in the pavement (Collop 1994).

Rutting models have traditionally been based on limiting the vertical stress or strain at the top of the subgrade using a model similar to the fatigue model (equation 3.8). These models assume that there is a unique relationship between the vertical compressive strain at formation level and the number of wheel loads to cause failure by excessive rutting. Rutting models are used in conjunction with the fatigue model for asphalt layers (Powell, et al. 1984).

Another rutting model is based on the “layer strain” approach (Collop 1994). In this approach, the model accounts for rutting in all the pavement layers by assuming either a linear or non-linear relationship between the elastic stress field and vertical permanent deformation in each layer. Another type of rutting model is based on the visco-elastic creep behaviour of asphalt materials. This type of model assumes that ruts form primarily by plastic flow of the pavement materials (Shell International 1978, 1985).

Basic engineering research on the properties of hydraulic materials, asphalt, aggregate, and additives and their effects on specific distress mechanisms have significantly contributed to the ability of engineers to develop materials that will perform well under specific environmental and traffic conditions. Much of this progress has been possible through continuing and significant reductions in computing costs and improvements in laboratory testing technology (Epps, et al. 2000). However, much work still requires to be done in evaluating material response and pavement performance due to environmental effects, e.g. surface initiated cracking, thermal fatigue cracking, and age hardening of asphalt (European Commission - DGVII 2000). The analysis and modelling of road pavements becomes even more important with the changing nature of materials.

Many pavement materials are anisotropic, often as a result of the stress-strain conditions in three-dimensions over time, and none of the materials are homogeneous, many even consist of discrete particles. Boundary conditions are often quite complicated and different from the conditions assumed when undertaking theoretical analysis such as layered elastic theory. In addition; tyre contact pressure is non-uniform and the tyre contact area is not circular (European Commission - DGVII 2000, Ullidtz 1987).

With the advent of finite element methods (using appropriate decomposition into discrete elements) and fast computers new possibilities are opened up for material characterization, other than linear elasticity, where difficulties with subgrade characterization have been identified (European Commission - DGVII 1999, 2000). The analysis of road pavements has improved and modelling of pavement response to load and environmental effects is becoming easier. Application of basic knowledge from other fields, primarily mechanics of materials and statistics, is improving the understanding of the mechanisms that determine the performance of bituminous mixtures in the pavement structure.

One of the major challenges is to be able to distinguish the effects of all the complexities in the relationship between stress and strain to arrive at a more complete knowledge of material behaviour. This knowledge can then be used to identify simple yet effective approaches to designing and specifying mixtures with suitable structural characteristics. A reliable constitutive model must be capable of accounting for effects of temperature, loading rate and time, rest periods, ageing, and multilevel loads (Epps, et al. 2000). However, increased complexity can only be justified if the response predicted by the more complex models is significantly closer to the actual pavement response, than the response predicted by the simpler models. If the more complex models do not improve the agreement with the actual pavement response, then the simpler models are to be preferred.

Recently a number of mechanistic models have been developed that can deal with some aspects of non-linear, viscous/plastic behaviour of materials, with other features such as anisotropy, dynamic loads, granular (non-continuous) materials. However, these advanced methods were not applied in current daily pavement design practice. Hence, in Europe, research has involved developing and harmonising advanced models for analytical design of pavements and investigations into the performance of unbound granular materials (European Commission - DGVII 2000).

3.10 Pavement Design

The life of a road pavement is determined by two main factors: traffic weight and volume, and environmental effects, e.g. ultraviolet light which oxidizes bitumen, temperature cycles which cause cracking, moisture content which affects granular materials, and freeze/thaw cycles which disrupt layers by volume change of water in the layers.

Pavement design is the process of selecting the most economical combination of pavement layers (in terms of material types and layer thicknesses) to suit:

1. The subgrade
2. The cumulative traffic to be carried (present and future and their distributions, day and night)
3. The environmental conditions – notably moisture (especially thinly surfaced pavements with unbound granular bases and freeze/thaw cycles which disrupt layers by volume change of water in the layers) and temperature (e.g. temperature cycles which cause cracking).

Hence, to be able to undertake a suitable pavement design it is useful to know the following:

1. The function the pavement has to perform
2. How long the pavement has to perform this function
3. The acceptable terminal condition of the pavement.

In addition, the designer should have an understanding of the principles of asphalt mechanics, hydraulic bound materials technology, unbound aggregate technology, soil mechanics and stabilisation technologies. The design for road pavements must take into account the many uncertainties that exist such as predicting traffic volumes (present, future and their distributions, day and night), varying vehicle axle mass configurations, constituent material properties, seasonal effects (which may cause variation in in-situ conditions such as moisture content and freeze/thaw periods) and drainage ability.

The design specifies the quality of the materials to be used and the layer thicknesses, which has an impact on quantity. The under-design of pavement layers or poor specification of pavement materials can lead to premature road failures. Conversely, over-design of individual pavement layer thicknesses will lead, in effect, to material wastage. In addition, over-specification of material quality will lead to the wastage of high-grade materials, which should be reserved for more demanding road requirements.

There are generally two approaches to pavement design: empirical design and analytical (mechanistic) design. There is a third variant, sometimes referred to as semi-analytical design, which attempts to combine the advantages of empirical and analytical designs.

The basis for empirical pavement design is (past successful) experience, and would normally stipulate factors such as aggregate type, gradation, composition by mass of each constituent, binder type, test method, method of production. Empirical designs have the advantage of being simple to operate and, provided that there is a suitable supply of materials and unchanging conditions (e.g. weather, traffic, local materials, layer thicknesses), work very well. A weakness in empirical pavement design is that it is only valid for the conditions under which they were developed, i.e. they do not allow for innovation or (future) changes in condition of loading or environment. Pavement failures have often resulted, however, when this approach, established in one locality, has been transferred and applied in another, which may have totally different conditions, e.g. subgrade soils or climate (European Commission - DGVII 1999). These designs do not have a means of assessing materials (e.g. recycled and secondary materials) that do not comply with the “recipe”, but may well be satisfactory or even superior – and it may lead to the design of very conservative pavements, which are uneconomical.

The mechanistic design approach involves measuring performance properties of material components, structural analysis of candidate pavements and the prediction of their performance (structural integrity) from the structural analysis. The method involves selecting a trial pavement cross-section with consideration given to the number and thickness of each layer, the material types, material state conditions (density and moisture content), and material performance properties from laboratory or field tests and estimating load levels throughout the design life. Stresses and strains caused by the applied traffic loadings on the trial pavement (using a response model) are determined and the 'critical life' for selected layers is established, based on performance prediction models. If necessary, the pavement design is then revised and a further iteration of the cycle is conducted. A summary of the steps involved in the procedure is outlined below and shown as Figure 3.15 (European Commission - DGVII 2000).

1. Initial conditions and structures.
2. Geometry.
3. Traffic.
4. Material properties.
5. Climatic and environmental conditions.
6. Response model.
7. Stresses, strains and displacements.
8. Performance models.
9. Structural change.
10. Current condition.
11. Complete history of the pavement.

Figure 3.15 also indicates some parameters (e.g. traffic, environment, material properties) that must be considered in order to predict pavement response and performance. Stage 11 of Figure 3.15 implies the possibility to repeat many incremental loops in which the effect of the damage on the design elements 2, 4, and 8 is taken into account. In this procedure design elements 9 and 10 should include changes in the structural properties of the pavement materials in addition to damage. Mechanistic design methods assess material properties in relation to performance thus the design method can be exported to new environments such as increased or reduced temperatures, increased traffic, and new materials.

The general theoretical basis, and principal criteria, for mechanistic design is limiting the horizontal tensile strain (fatigue cracking) at the bottom of the asphalt layer and limiting the accumulation of vertical strain (pavement rutting) at the top of the subgrade (Brown 1996a, European Commission - DGVII 2000). This theoretical basis is shown as Figure 3.16. Satisfactory levels of resilient modulus are required for materials used in road pavement layers in order to reduce strains imposed by traffic loadings. Numerous design methods (using linear elastic theory) have been developed that incorporate this concept.

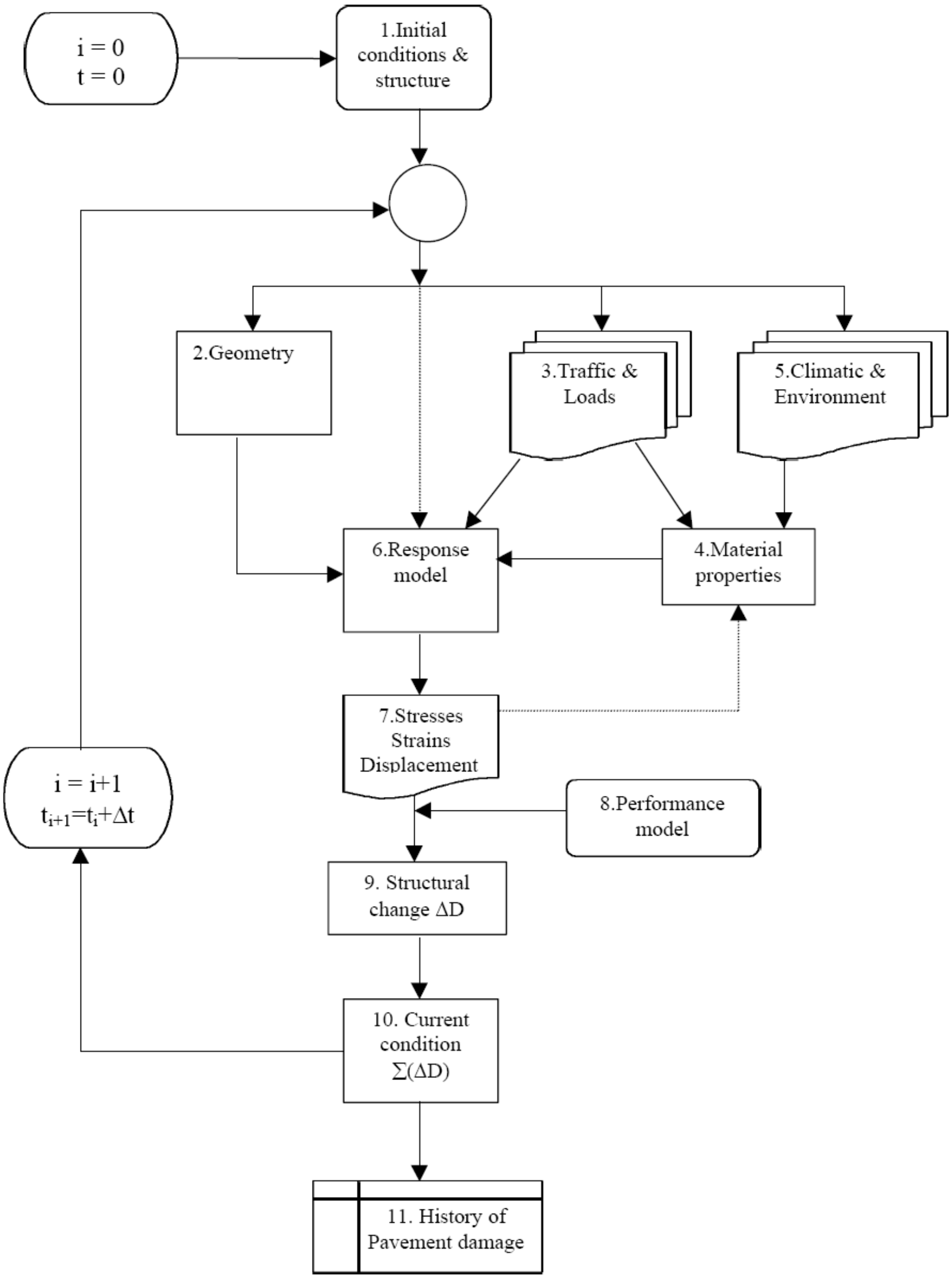


Figure 3.15: Flow chart iteration in mechanistic (incremental) pavement design (European Commission - DGVII 2000)

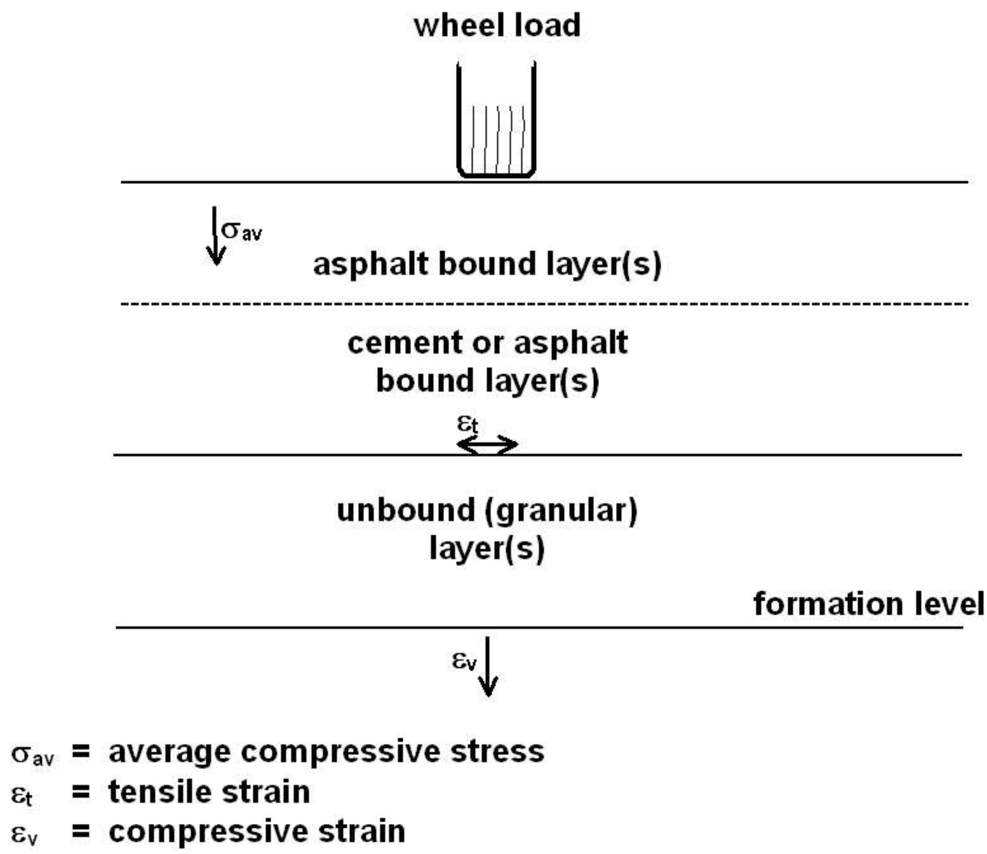


Figure 3.16: Theoretical basis for critical stresses/strains in road pavements

However, from observations of pavement deteriorations, cracking from the bottom of the base and rutting from the top of the subgrade rank relatively low compared to other forms of pavement deterioration, such as asphalt rutting, loss of skidding resistance, surface cracking, and longitudinal unevenness (European Commission - DGVII 2000). Surface cracking as a deterioration criterion cannot be explained using only the tensile stress at the bottom of the bound layers because the horizontal stresses and strains generated in the upper half of the asphalt layer are compressive (Collop 1994). More research is required into developing new improved models for pavement design, which incorporate observed deterioration mechanisms that are higher up the ranking. Details on pavement design methods used in different parts of the world can be found in the literature (European Commission - DGVII 2000, Mundy 2002).

Historically, the design of roads has been principally based on experience and knowledge, but research is attempting to provide understanding of materials through targeted laboratory and field based testing programs in order that designs can be better, and more reliably, undertaken. A principal means to achieving this is by developing a more scientific understanding of the materials by which some of the inefficiencies of empiricism could be addressed.

3.11 Summary

The broad issues that have been addressed in this chapter are road pavement structure and materials technology (material properties, technology development, materials testing, modelling and design). A description of typical road pavement constructions has been presented; in general road pavements are considered to provide two main functions: surface and structural. Surface functions include providing safety and comfort while structural functions are associated with material properties such as strength and stiffness.

Material properties have been discussed and the development of materials technology (for bound and unbound materials) has been summarised. Materials technology for road pavements has advanced over many years in asphalt, hydraulic bound and unbound granular materials – there is greater acceptance in the use of recycled and secondary materials but more needs to done to increase this acceptance – this can be achieved through an understanding of the materials science.

Pavement materials testing has been discussed and, subsequently, modelling and design of pavements described. It is important when measuring the performance of pavement materials that the test method should model as closely as possible the actual loading conditions of the pavement in the environment. The proper selection of test conditions and representation of the stress states in the actual pavement are critical to their success.

There have been advances in structural analysis and design of road pavements, which take into consideration fundamental material properties. The measurement of fundamental properties offers the advantage of being able to represent a variety of loading and environmental conditions through modelling.

On the subject of materials science, the following can be summarised from this chapter.

1. There is a wide range of cultural, geological, and environmental factors, and hence a different emphasis in road construction and maintenance requirements.
2. It is potentially feasible to have consistency in material science, by specifying two main functions:
   (i) Surface function, e.g. riding comfort, safety, drainage
   (ii) Structural function, e.g. prevent subgrade from being overstressed, withstand traffic loading for the design period.
3. A range of performance requirements have been highlighted and some of these are outlined below:
   (i) Density
   (ii) Durability
   (iii) Fatigue resistance
   (iv) Hardness
   (v) Moisture movement
   (vi) Permanent deformation resistance
   (vii) Permeability
   (viii) Porosity
   (ix) Skidding resistance
   (x) Stiffness
   (xi) Strength

   These requirements, which cover bound, unbound, primary, recycled and secondary materials, are tested through an understanding of the materials science. A materials science appraisal is presented in Chapter 4.
4. Models of pavement performance need to be simple since the uptake in the use of complex models daily practice is very low. Increased complexity can be justified if the response predicted by the more complex models is significantly closer to the actual pavement response, than the response predicted by the simpler models. If the more complex models do not improve the agreement with the actual pavement response, then the simpler models are to be preferred.

Materials used in road pavements can typically be classified into three fundamental broad groups, based on similar constituents and behavioural properties. These groups are:

(i) Ceramic-type materials, e.g. concrete

(ii) Metallic-type materials, e.g. steel reinforcement

(iii) Polymeric-type materials, e.g. bitumen

These groups are very similar to classifications in materials science (Shackelford 2000, Young, et al. 1998). However, there are subtle differences that are proposed in this research, with more details given in Chapter 4. Essentially, the group philosophy is to allow evaluation of material performance to be rational and based on material-type, not necessarily on whether the material is primary, recycled or secondary material. This will support the engineering decision-making process for selecting materials for use in roadways.

From the foregoing, and complexities of road pavement construction and materials, it would be useful to have a consistent and rational materials science evaluation of roadway materials. The development of a consistent approach is described in Chapter 4.

Chapter 4 Development of Materials Science Appraisal

4.1 Introduction

This chapter describes the development of the materials science appraisal, which is based on proposing new theories from old theories. The concept defines how materials science can be used to achieve engineering sustainability in road pavement construction and maintenance, while the resulting appraisal is a systematic step-by-step procedure for evaluating the extent of this sustainability. Knowledge of the extent of this sustainability will assist in the engineering decision-making in the use of these materials.

The concept for the innovative materials science appraisal has been developed from the detailed literature review in Chapter 2 and Chapter 3. The novel methodology of the materials science appraisal, which is a further development from the concept, consists of components that are interdependent and interactive in a collective effort to achieve engineering sustainability with road pavements. The development of the novel materials science appraisal allows the use of existing, new and future technologies to create adequate products for road pavement systems.

4.2 Development Process

The process used in developing the materials science appraisal methodology is shown as Figure 4.1, the process has been adapted from descriptions given elsewhere (Fellows and Liu 1997). The development process shown as Figure 4.1 is considered to be appropriate in a first stage development of the appraisal. However, further development of the appraisal may include “feedback” to the literature review which can further inform the appraisal. The materials science concept (section 4.3) is unlikely to require any further development. The stages (Figure 4.1) involved in developing the appraisal are outlined below in further detail:

1. **Research objectives and literature review**: The initial stage involves making decisions about the objectives and scope of the research followed by a literature investigation of existing theories, principles and practices. These issues are highlighted in Chapter 1 to Chapter 3.

2. **Development of materials science concept and appraisal:** Details on the development of the concept are given in section 4.3. The development of the materials science appraisal is detailed in section 4.5. This stage involves development of the basic structure from the materials science concept. It also involves components, establishing and integrating interdependencies and interactions between individual components, and organisation into a unified logical structure.

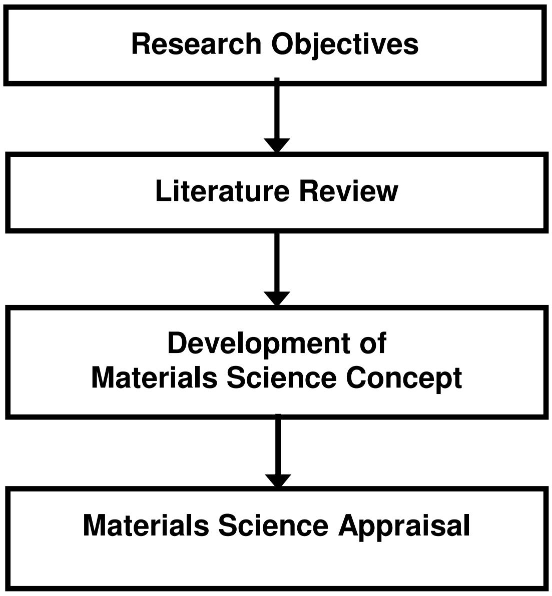


Figure 4.1: The process used for developing materials science appraisal

4.3 Innovative Materials Science Concept

Systematic studies of key technical properties of materials are required, as is experimental data that gives the widest possible limits within which materials can be used under different traffic conditions and in different climates (including climate variation within the same locality). This should allow performance criteria to be prepared which will permit and promote the use of a variety of products.

The potential for using materials must continually be assessed to develop new materials and technologies. For instance, it is possible that another industry's waste or by-product material may emerge as the construction industry's useable material. An example of this is blast-furnace slag, which can be used as an aggregate or as a cement replacement material. Both of these materials are useful in road construction applications, and until this discovery had been made most blast furnace slag was discarded.

The choice and sophistication of products and techniques will become wider and more complex, with the development of technologies including recycling of construction materials and cold-treatment applications (Griffin, et al. 2000).

There is a need for construction practitioners (clients, consultants, contractors and suppliers) to have a good general knowledge of properties of materials and their use so that the right choices can be made. Consideration of materials within broad groups that exhibit similar properties and behaviour reduces complexity in decision-making for construction practitioners.

If a wide-ranging and appropriate knowledge is applied within a suitable framework then solutions become more obvious and less difficult. Hence a set of principles that links materials science to the creative use of materials is necessary. The concept of a simplified classification is proposed. The development of the materials science concept comprises classification of material types and performance of road products (the evaluation of which is based on pavement distress and the material type classification).

The materials classification concept is a step towards evaluating all materials more rationally irrespective of the material source, and should also encourage the use of blended products, especially where this is a less expensive alternative, e.g. blends of demolition arisings, blends of primary and recycled, and blends of crushed concrete and crushed asphalts.

The materials science classification concept proposes that, on a macroscopic scale, road materials can potentially be classified from three fundamental material-types, namely Ceramic-type, Metallic-type, and Polymeric-type. This concept is very similar to how materials are generally classified in materials science (Shackelford 2000, Young, et al. 1998). The novel ternary diagram (see Figure 4.2), which has been developed by the author, has the apexes corresponding to the three fundamental material-types, which have similar constituents and behavioural properties. The novel concept, consequently, classifies road materials into seven broad groups (Figure 4.2). However, it is considered that, in addition to the material-type, the dominant effect can be affected by the material-type that is the continuous phase (Abo-Qudais, et al. 1999, Airey and Rahimzadeh 2004, Merrill, et al. 2004). For example, approximately 75% of the total volume of bituminous mixtures is aggregate, but bitumen may exert a greater influence on the deformation characteristics than the aggregate (Ahlrich 1995). Also, the recent UK guide on cold recycled materials for road pavement maintenance defined material family names based on characteristics of the stabilising agents (i.e. the presence of cement and/or asphalt binder) (Merrill, et al. 2004).

The materials classification concept can include primary products, non-primary products or a blend of primary and non-primary products. The classification is especially useful when it comes to recycled and secondary materials where there is a wide range. A description of the nature of the different material-types is given in sections 4.3.1 to 4.3.4.

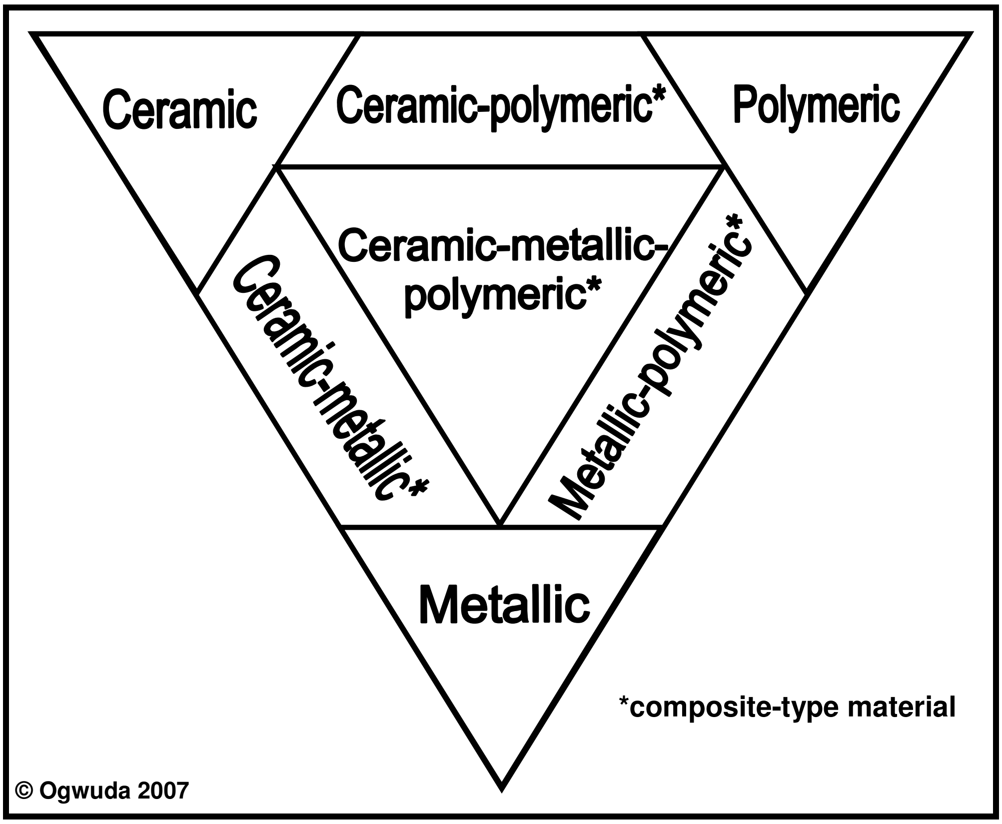


Figure 4.2: Material-type classification concept

4.3.1 Ceramic-type Materials

Ceramic-type materials are inorganic materials, are generally brittle, have limited elasticity and have low fatigue resistance. Some ceramic-type materials have binder properties, which could be hydraulic or non-hydraulic – and some ceramic-type materials may have pozzolanic properties. Ceramic-type materials generally have good creep properties in the short term, but over longer periods (say many years) may suffer creep. Durability is dependent on water (subject to moisture movement), temperature (low thermal movement), and some chemicals. Ceramic-type materials are relatively hard, porous and permeable, and have relatively high stiffness. These materials generally have relatively high compressive strength, low tensile strength and low toughness. Examples of ceramic-type materials are Pulverized Fuel Ash (PFA), glass, cement, crushed rock aggregates and soil.

4.3.2 Metallic-type Materials

Most metallic-type materials are generally inorganic, ductile, and subject to creep and thermal movement at elevated temperatures (e.g. close to their melting point). Most metallic materials have relative high density and corrosion can be a major problem. Most of these materials have a certain degree of elasticity with ductile materials having better fatigue properties. Most have a certain degree of plasticity but will depend on whether the material is ductile (high plasticity) or brittle (low plasticity). Metallic-type materials have relatively good hardness properties, are generally resistant to moisture movement, and are generally non-permeable and non-porous. Metallic-type materials have relatively high stiffness and generally good tensile strength. Toughness depends on whether a material is brittle (low toughness) or ductile (high toughness). Examples of metallic-type materials are aluminium, copper, and steel.

4.3.3 Polymeric-type Materials

Polymeric-type materials are mainly organic materials and are ductile, but some materials can be brittle, more especially at lower temperatures. These materials can have binding properties, are generally subject to creep (especially when exposed to elevated temperatures), have relatively low hardness and are generally lightweight. The main issue with these materials is environmental degradation (e.g. U-V radiation, oxidation); resistance to fire can be an issue (e.g. combustion, fire spread, and oxygen). Polymeric materials have a high elasticity and plasticity, but plasticity would depend on whether a material is ductile (high plasticity) or brittle (low plasticity). Polymeric-type materials generally have good toughness, but may have poor toughness if the material is brittle. Polymeric-type materials have good fatigue properties, if the material is flexible, are generally resistant to moisture movement, and are generally non-permeable and non-porous. Polymeric materials have relatively high thermal movement, and relatively low stiffness and strength. Viscosity of the material varies depending on nature of material, temperature and applied loading. Examples of polymeric-type materials are bitumen, paints and polymers.

4.3.4 Composite-type Materials

Composite-type materials are combinations of the other material-types and can be described in terms of the matrix, which is the continuous phase and inclusions (which are dispersed within the matrix). The rationale for composite-type material would be to produce a material that combines the best properties of each individual component, and is superior to either of the separate components. From Figure 4.2, composite-type materials could be one of the following:

1. Ceramic-metallic-type
2. Ceramic-polymeric-type
3. Metallic-polymeric-type
4. Ceramic-metallic-polymeric-type

4.4 Road Pavement Distress

In assessing road materials it is considered that there are three main modes of pavement distress that affect performance, namely: ***fracture***, ***disintegration***, and ***distortion***. New definitions, developed by the author, for fracture, disintegration and distortion are given in sections 4.4.1 to 4.4.3. The new definitions have been developed from those given by O'Flaherty (1988), which cover only bituminous surfacings. The new definitions now encompass all forms of materials used in road pavement construction and maintenance.

4.4.1 Fracture

Fracture is cracking (initiation and propagation) of the pavement, which is a manifestation of volume change, of excessive strain under given traffic loadings, and of differential foundation support conditions (differential movement). Fracture can also be a manifestation of environmental conditions (thermal changes and moisture damage).

4.4.2 Disintegration

Disintegration is the gradual break-up of the pavement material under the abrasive and dynamic action of traffic and under the mechanical or chemical actions of weathering. It is evidenced by the wearing or breaking away of material ranging from small to large particles. Disintegration can result from such actions as loss of bonding, chemical reactivity, traffic abrasion, aggregate degradation, poor consolidation/compaction or binder aging.

4.4.3 Distortion

Distortion is the deformation of the pavement under traffic loading and also due to environmental conditions. It can be described as the vertical and lateral deformation manifested at the pavement surface under conditions of heavy or repeated traffic loadings, loss of foundation support or differential expansion and settlement. It is evidenced by plastic deformation within a pavement structure, or by localised depression in wheel tracks or by undulating changes in elevations conforming to compressible or expansive foundation soils. Distortion can result from such things as excessive loading, creep, densification, consolidation, swelling, or frost action.

4.5 Novel Methodology for Materials Science Appraisal

4.5.1 Methodology Issues

The methodology which has similar appraisal issues to the materials science appraisal in this thesis is that developed by Torring (Torring 2001). Torring developed a decision-making system for managing construction and demolition waste, identifying parameters required to create a balance between economic and environmental constraints. Torring specifically investigated operations, costs, environmental indicators, the role of different stakeholders, and quality control. These were factors from case study viewpoints.

The materials science appraisal is based on materials science, which makes it principally different from Torring’s methodology (based on economics and environmental constraints). However, specific and related conditions from Torring’s methodology are relevant to the materials science appraisal. These conditions have been adapted and used in the development of the appraisal, and are presented below:

1. Due to the varied backgrounds and expertise of decision-makers, the appraisal is developed so that the level of technical detail is readily understandable – but with the recognition for the need for specialists to be consulted as necessary.
2. It is proposed that the appraisal allows the user to undertake sensitivity changes and allowing elements of reality to be evaluated.
3. The appraisal would broadly be guided along three pathways:
   (i) Selective: where solutions to the problem exist and a choice is made between alternative products.
   (ii) Creative: solutions do not exist and alternative products need to be developed.
   (iii) A Combination of (i) and (ii).
4. Pitfalls in the appraisal include:
   (i) Tunnel vision: A need to justify the decision by manipulation of the facts (emphasis on the pros, ignoring cons)
   (ii) A "halo/horns" effect, i.e. agreeing with the products that are liked and admired; and vetoing products that are disliked.

4.5.2 Detailed Methodology

The methodology involves development of the performance requirements for a road product. Following on from the performance requirements is the development of the materials science of the road product and, subsequently, evaluation of the potential performance of the product. The methodology (sections 4.5.2.1 to 4.5.2.6) is illustrated in Figure 4.3.

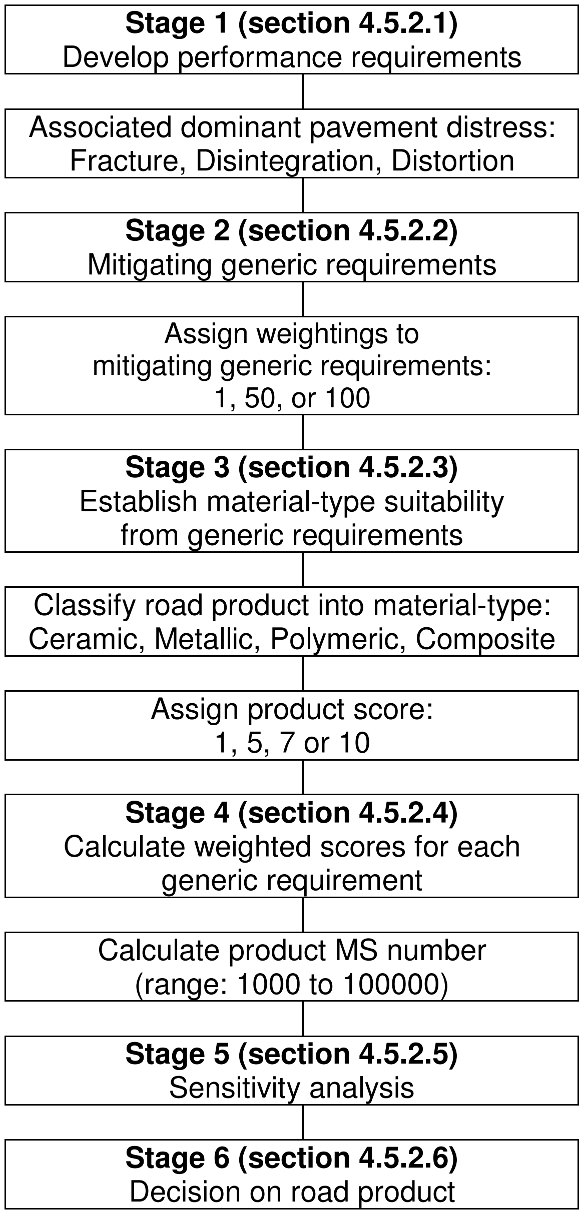


Figure 4.3: Methodology for materials science appraisal

4.5.2.1 Stage 1: Performance Requirements and Associated Dominant Pavement Distress

Develop performance requirements for the road product application and categorise these requirements into the associated dominant form of pavement distress – fracture, distortion or disintegration (see section 4.4). Table 4.1 lists potential performance requirements and their associated dominant pavement distress; these highlight the major defect that would arise with a specific poor performance requirement. For example, if a performance requirement were fatigue resistance then the dominant pavement distress associated with low fatigue resistance would be fracture.

Table 4.1: Potential road pavement performance requirements and dominant pavement distress

Stage 1 (section 4.5.2.1)			
Performance requirement	**Dominant pavement distress associated with low performance**		
	Fracture	**Disintegration**	**Distortion**
Cohesion		✓	
Low Brittleness	✓		
Chemical Degradation Resistance		✓	
Creep Resistance			✓
Adequate Density			✓
Adequate Elasticity	✓		
Low Fatigue	✓		
Adequate Hardness (abrasion/polishing)		✓	
Low Moisture Movement			✓
Adequate Stiffness			✓
Adequate Strength			✓
Low Thermal Movement			✓
Adequate Toughness	✓		

4.5.2.2 Stage 2: Mitigating Generic Requirements and Weighting

This stage involves identifying mitigating generic requirements for each distress and assigning weightings to each mitigating generic requirement. The mitigating generic requirements, which are considered to reduce the three main modes of pavement distress, i.e. fracture, disintegration and distortion, are shown in Table 4.2. These requirements have been developed from pavement deficiencies related to bitumen durability, reported by Vallerga (1981). Table 4.2, which the author has developed, incorporates all forms of pavement distress, whereas Vallerga developed pavement deficiencies in relation to bitumen only. Thus, pavement distress and mitigation not only covers bitumen, but also includes cement and other hydraulic binders, aggregates (primary, recycled and secondary), unbound mixtures and bound mixtures.

Table 4.2: Pavement distress and mitigating generic requirements

Stage 2 (section 4.5.2.2)	
Pavement distress	**Mitigating generic requirements**
Fracture	High elasticity
Fracture	High plasticity (ductility)
Fracture	High toughness

Table 4.2: Pavement distress and mitigating generic requirements

Stage 2 (section 4.5.2.2)	
Pavement distress	**Mitigating generic requirements**
Fracture	Low brittleness
Fracture	Low creep movement
Fracture	Low fatigue
Fracture	Low moisture movement
Fracture	Low thermal movement
Distortion	High density
Distortion	High interparticle friction
Distortion	High stiffness
Distortion	High strength
Distortion	Low creep movement
Distortion	Low moisture movement
Distortion	Low thermal movement
Disintegration	High cohesion (bonding)
Disintegration	High hardness (abrasion/polishing)
Disintegration	Low chemical degradation
Disintegration	Low Porosity/Permeability

Weightings are assigned to mitigating generic requirements, based on the hierarchical importance of generic requirements within a particular performance requirement, which will include product application. The weighting values of 1, 50 or 100 have been developed, with 100 being of high importance and 1 being of low importance. The values of weightings have been based on 1670 combinations (details of which are given in Appendix A); and these weighting values give distinct discriminating effects of the important and non-important generic requirements. At least one generic requirement should have a weighting of 100; otherwise, the reasoning behind the evaluation would have to be questioned. The assigning of weightings should be done with care to avoid any bias. Kepner and Tregoe (1997) have reported on instances that can lead to bias:

(i) Too many high values may indicate either unrealistic expectations or a faulty perception of which requirements can guarantee success.

(ii) Too many low values suggest that unimportant details may be overwhelming the analysis.

(iii) Too many objectives reflecting the vested interest of a single stakeholder may lead to an unworkable decision – this is especially true if other stakeholders are equally affected by the final decision.

(iv) Loaded requirements that guarantee a smooth passage for a particular product and “penalise” others can make a mockery of the analysis.

4.5.2.3 Stage 3: Material-type and Product Score

This stage involves establishing the material-types that are more suitable for each generic requirement. Table 4.3 shows material-type suitability for mitigating generic requirements. Suitability is based on the material-type definitions given in sections 4.3.1 to 4.3.4. This stage also involves classifying road products into one of seven broad material-types as depicted in the "Material-type classification" ternary diagram (Figure 4.2). For each generic requirement, product scores are assigned to the road product (based on classification of road product and material-type suitability criteria) – better scores will be awarded to the more suitable products. Product score values of 1, 5, 7 or 10 have been developed, with 10 being the most suitable material-type and 1 being of low suitability. The values of product scores have been based on 1670 combinations of product scores, details of which are given in Appendix A; and these product scores give distinct discriminating effects of different material-type.

Table 4.3: Pavement distress, mitigating generic requirements and material-type suitability

Stage 2 (section 4.5.2.2)		Stage 3 (section 4.5.2.3)	
Pavement distress	**Mitigating generic requirements**	**Materials more suited**	**Materials less suited**
Fracture	High elasticity	Metallic-type Polymeric-type	Ceramic-type
Fracture	High plasticity (ductility)	Metallic-type Polymeric-type	Ceramic-type
Fracture	High toughness	Metallic-type Polymeric-type	Ceramic-type
Fracture	Low brittleness	Metallic-type Polymeric-type	Ceramic-type
Fracture	Low creep movement	Ceramic-type	Metallic-type Polymeric-type
Fracture	Low fatigue	Metallic-type Polymeric-type	Ceramic-type
Fracture	Low moisture movement	Metallic-type Polymeric-type	Ceramic-type
Fracture	Low thermal movement	Ceramic-type Metallic-type	Polymeric-type
Distortion	High density	Ceramic-type Metallic-type	Polymeric-type
Distortion	High interparticle friction	Ceramic-type	Metallic-type Polymeric-type
Distortion	High stiffness	Ceramic-type Metallic-type	Polymeric-type
Distortion	High strength	Ceramic-type Metallic-type	Polymeric-type
Distortion	Low creep movement	Ceramic-type	Metallic-type Polymeric-type
Distortion	Low moisture movement	Metallic-type Polymeric-type	Ceramic-type

Table 4.3: Pavement distress, mitigating generic requirements and material-type suitability

Stage 2 (section 4.5.2.2)		Stage 3 (section 4.5.2.3)	
Pavement distress	**Mitigating generic requirements**	**Materials more suited**	**Materials less suited**
Distortion	Low thermal movement	Ceramic-type Metallic-type	Polymeric-type
Disintegration	High cohesion (bonding)	Ceramic-type Polymeric-type	Metallic-type
Disintegration	High hardness (abrasion/polishing)	Ceramic-type Metallic-type	Polymeric-type
Disintegration	Low chemical degradation	Ceramic-type	Metallic-type Polymeric-type
Disintegration	Low Porosity/Permeability	Metallic-type Polymeric-type	Ceramic-type

4.5.2.4 Stage 4: Materials Science (MS) Number

Calculate weighted scores for each generic requirement of the road product. The weighted score is calculated using equation 4.1.

$$\text{Weighted Score} = \text{generic requirement weighting} \times (\text{product score})^2 \tag{4.1}$$

The product score is squared to increase its effect on the sensitivity of the overall performance appraisal; based on 1670 combinations of product scores, details of which are given in Appendix A.

Once the weighted scores have been calculated then the Materials Science (MS) number can be computed. The MS number (which ranges from 1000 to 100,000) is computed using equation 4.2.

$$\text{MS Number} = \left(\frac{\text{actual sum of weighted scores}}{\text{ideal sum of weighted scores}}\right) \times 100{,}000 \tag{4.2}$$

The higher the MS number the better the road product. The ideal sum of weighted scores is based on product scores for all generic requirements being equal to 10 (10 being the best score for material-type). A factor of 100,000 is applied so that the MS number will be sensitive to changes in generic requirement weighting and product score. Again, this has been based on 1670 combinations of product scores, details of which are given in Appendix A.

Figure 4.4 gives the threshold values of MS numbers in relation to red, yellow and green zones. Green represents the better road product (MS in the range 70,000 to 100,000); the red represents the worse road product (MS in the range 1,000 to 30,000) and intermediate between green red and green is yellow (MS in the range 30,000 to 70,000). The yellow threshold range (MS in the range 30,000 to 70,000) is where most road products are expected to perform given a balance of economic and performance factors. The green threshold range (70,000 to 100,000) would be for more expensive products while the red threshold range (1,000 to 30,000) would be for products that are relatively cheap and have exceptionally low performance.

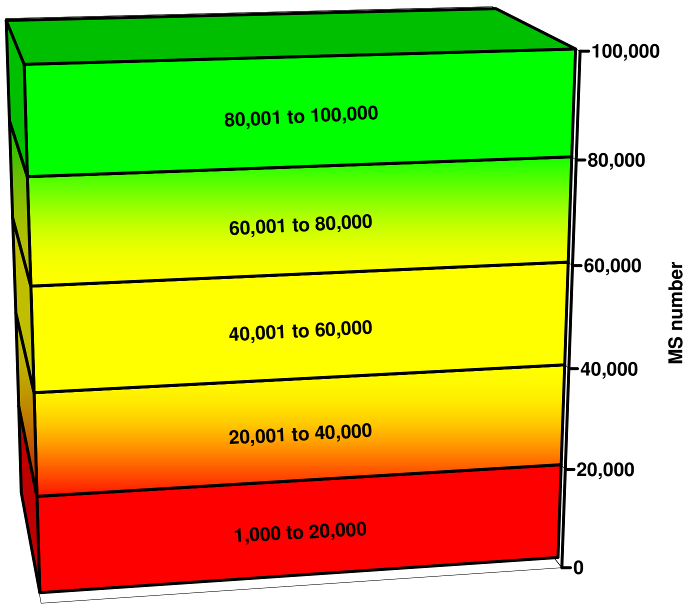


Figure 4.4: MS range (red, yellow and green zones)

The red, yellow and green zones (and their thresholds) are defined to give a basis for decision-making. In the green zone, the product should not present major difficulties in performance. The yellow zone is a warning to the decision-maker that although performance may be satisfactory, the road product will need to be monitored periodically. The red zone should give the decision-maker serious cause for concern.

4.5.2.5 Stage 5: Sensitivity Analysis

The sensitivity analysis allows an evaluation of the effect of changes in generic requirement weighting and product score on the MS number. The generic requirement weightings that deserve the most attention should depict the greatest effect on the MS number and the products with uncertainty in product score should be analyzed by sensitivity analysis. The following are some issues that can be addressed by sensitivity analysis.

(i) The risks associated with a road product that is too close to the minimum performance requirements.

(ii) Risks associated with invalid information about the road product (e.g. excess traffic loading, improper design).

(iii) Risks in the short- and long-term associated with the road product (e.g. random material defects, workmanship, poor drainage).

Table 4.4 shows the effect of varying the product score on the MS number. The magnitude of the MS number is influenced by the generic requirement weightings of 50 and 100, and whichever product score has at least a 10% presence in these weightings. Based on 1670 combinations, a summary of how the MS number is influenced by the percentage of product scores at weightings of 50 and 100 is shown as Table 4.4 (details of the combinations are given in Appendix A). Table 4.4 shows that the lower the product score the lower the MS number, with product scores that predominantly 1, 5 and 7 likely to be in the red zone. Product scores that are predominantly 5 and 7 are in the yellow zone, while product scores that are predominantly 7 and 10 are likely to be in the red zone.

4.5.2.6 Stage 6: Road Product Decision

Engineering decision-making on road product, preferably based on the best-balanced choice. Assistance in the engineering decision-making can be through a first screening process, with road products that pass this first screening process being subject to further investigation – possibly reusing the appraisal more rigorously. Further engineering decisions can be based around eliminating candidate road products that do not pass the first screening process – but constraints or conditions could be changed during the appraisal process. A further engineering decision-making could be based on appraising road products, that pass the first screening test, more rigorously – in conjunction with materials analysis and testing. Road products with marginal feasibility could undergo further rigorous evaluation in specific areas from where the marginal feasibility has arisen.

Table 4.4: Probable MS number for product score combinations at generic requirement weightings of 50 and 100 (section 4.5.2.5)

Range of MS Number	Product Scores that have a 10% minimum presence at Generic Requirement Weightings of 50 and 100														
	1	1,5	1,7	1,5,7	5	5,7	1,5,10	1,10	7	1,5,7,10	1,7,10	5,7,10	5,10	7,10	10
1000 to 20000	X	X	X	X											
20001 to 40000			X	X	X	X	X	X							
40001 to 60000						X	X	X	X	X	X	X	X		
60001 to 80000								X			X	X	X	X	
80001 to 100000													X	X	X

X indicates more probable value of MS Number

A spreadsheet has been developed for the evaluation of information in relation to stages 1 to 5 of the materials science appraisal. The spreadsheet uses equations 4.1 and 4.2 to calculate the weighted score and MS number, respectively. A snapshot of the spreadsheet is shown as Figure 4.5. The violet-coloured cells in the spreadsheet are for input information, i.e. performance requirement, generic requirement weighting and product score. "Errors" are displayed if the wrong values are input for generic requirement weighting and product score. Once the input values are entered, the spreadsheet will calculate the weighted scores and MS number. The spreadsheet is especially useful in sensitivity analysis, of generic requirement weighting and product scores, which is a key aspect of the engineering decision-making process.

Stage 1		Stage 2		Stage 3							Stage 4				
Performance requirement	Dominant pavement distress	Mitigating generic requirements	Generic requirement weighting	Material more suited	Material less suited	product score					weighted score				
						product 1	product 2	product 3	product 4	product 5	product 1	product 2	product 3	product 4	product 5
Low Fatigue	Fracture	High plasticity (ductility)	1	metallic-type polymeric-type	ceramic-type	10	1	10	7	5	100	1	100	49	25
Low Fatigue	Fracture	Low fatigue	100	metallic-type polymeric-type	ceramic-type	10	1	10	7	10	10000	100	10000	4900	10000
Low Fatigue	Fracture	Low brittleness	1	metallic-type polymeric-type	ceramic-type	10	1	10	7	5	100	1	100	49	25
Low Fatigue	Fracture	High toughness	100	metallic-type polymeric-type	ceramic-type	10	1	10	10	10	10000	100	10000	10000	10000
Low Fatigue	Fracture	Low moisture movement	50	metallic-type polymeric-type	ceramic-type	10	1	10	10	10	5000	50	5000	5000	5000
Low Fatigue	Fracture	Low thermal movement	100	ceramic-type metallic-type	polymeric-type	10	1	10	7	10	10000	100	10000	4900	10000
Low Fatigue	Fracture	Low creep movement	100	ceramic-type	metallic-type polymeric-type	10	1	10	10	10	10000	100	10000	10000	10000
Low Fatigue	Fracture	High elasticity	50	metallic-type polymeric-type	ceramic-type	10	1	10	7	10	5000	50	5000	2450	5000
Adequate Hardness (abrasion/polishing)	Disintegration	High cohesion (bonding)	100	ceramic-type polymeric-type	metallic-type	1	1	10	7	10	100	100	10000	4900	10000
Adequate Hardness (abrasion/polishing)	Disintegration	High hardness (abrasion/polishing)	50	ceramic-type metallic-type	polymeric-type	10	1	10	5	10	5000	50	5000	1250	5000
Adequate Hardness (abrasion/polishing)	Disintegration	Low Porosity/Permeability	100	metallic-type polymeric-type	ceramic-type	10	1	10	5	10	10000	100	10000	2500	10000
Adequate Hardness (abrasion/polishing)	Disintegration	Low chemical degradation	100	ceramic-type	metallic-type polymeric-type	1	1	10	10	10	100	100	10000	10000	10000
Adequate Strength	Distortion	High interparticle friction	50	ceramic-type	metallic-type polymeric-type	10	1	10	10	10	5000	50	5000	5000	5000
Adequate Strength	Distortion	High stiffness	100	ceramic-type metallic-type	polymeric-type	1	1	10	5	10	100	100	10000	2500	10000
Adequate Strength	Distortion	High density	100	ceramic-type metallic-type	polymeric-type	7	1	10	5	10	4900	100	10000	2500	10000
Adequate Strength	Distortion	Low moisture movement	100	metallic-type polymeric-type	ceramic-type	5	1	10	1	10	2500	100	10000	100	10000
Adequate Strength	Distortion	Low thermal movement	50	ceramic-type metallic-type	polymeric-type	10	1	10	1	7	5000	50	5000	50	2450
Adequate Strength	Distortion	Low creep movement	100	ceramic-type	metallic-type polymeric-type	5	1	10	10	10	2500	100	10000	10000	10000
Adequate Strength	Distortion	High strength	50	ceramic-type metallic-type	polymeric-type	10	1	10	1	10	5000	50	5000	50	5000
										actual sum	90400	1402	140200	76198	137500
										ideal sum	140200	140200	140200	140200	140200
										MS number	**64479**	**1000**	**100000**	**54350**	**98074**

Figure 4.5: Snapshot of spreadsheet for materials science appraisal

4.6 Summary

The materials science concept has been described. A proposed simplified classification for materials-type has been presented; the simplicity is in having three fundamental major groupings for material-types, namely Ceramic-type, Metallic-type, and Polymeric-type. The concept of a simplified classification for materials should reduce complexities in understanding behavioural properties of materials; and will be of benefit to stakeholders involved in road construction and maintenance. Road pavement distress is considered to occur in three main modes, viz: fracture, disintegration, and distortion – and there are associated mitigating generic requirements.

A novel materials science appraisal of roadway materials has been developed. The methodology comprises 6 stages, as follows:

1. Establish performance requirements and categorise into dominant form of pavement distress - fracture, disintegration and distortion.
2. Identification and weighting of mitigating generic requirements
3. Evaluation of material-type suitability and scoring of road product
4. Calculation of weighted scores and MS number
5. Sensitivity analysis.
6. Engineering decision-making on road product.

Consequently, the material-type classification can be used to advise on constituents and behavioural properties, and this can be linked to potential road performance using the appraisal methodology outlined above. The appraisal allows current, alternative and innovative use of materials technology that will provide best value longer life road constructions. Sensitivity analysis can be incorporated in the procedure, hence engineering decisions can be made and economic and environmental alternative road products can be evaluated. The application of the novel concept and innovative materials science appraisal is presented in Chapter 5.

Chapter 5 Appraisal of Recycled Construction Arisings

5.1 Introduction

This chapter demonstrates the application of the novel concept of the materials science appraisal to recycled construction materials. Over a three year period, laboratory tests on construction arisings have been undertaken and are reported elsewhere (Aznar 1999, Carr 1997, Chin 2001, Cooney 1998, Hayes 2001, Lim 1999, Raravula 1998, Reid 1998). These tests include grading, plasticity, compaction (density-moisture content relationship), Aggregate Impact Value (AIV), Ten percent Fines Value (TFV), flakiness index, bitumen softening and penetration tests, water absorption, concrete mix design, plasticity tests, California Bearing Ratio (CBR), shear strength and the Marshall test for bituminous mixes. This chapter shows how the materials science appraisal can be applied to the essence of laboratory testing. The results from the materials science appraisal is the calculation of the MS number (red, green or red zone), which, together with sensitivity analysis, gives an informed engineering decision on product choice.

5.2 Overview of Construction Arisings

Two types of construction arisings have been used for the materials science evaluation – demolition arisings and roadway arisings.

5.2.1 Demolition Arisings

Two 17-storey residential buildings in the Ardler area of Dundee (Scotland) were demolished, producing approximately 60,000 tonnes of demolition rubble. The demolition arisings used in this research consisted of mainly concrete, clay bricks and clinker blocks with concrete forming most of the arisings. The amounts of "contaminants" in the demolition arisings were fairly low and consisted of mainly timber plus smaller proportions of plastics, metal and glass. Hence the demolition arising is a ceramic-type material (section 4.3.1). Figure 5.1 and Figure 5.2 show typical ceramic-type materials and contaminants, respectively, in the demolition arisings. Production of the demolition arisings have been reported by Ogwuda, et. al. (1998) and are given in Appendix C. Sampling of the demolition arisings are given in

Appendix B. Table 5.1 gives a summary of the demolition arisings from the production and sampling process.

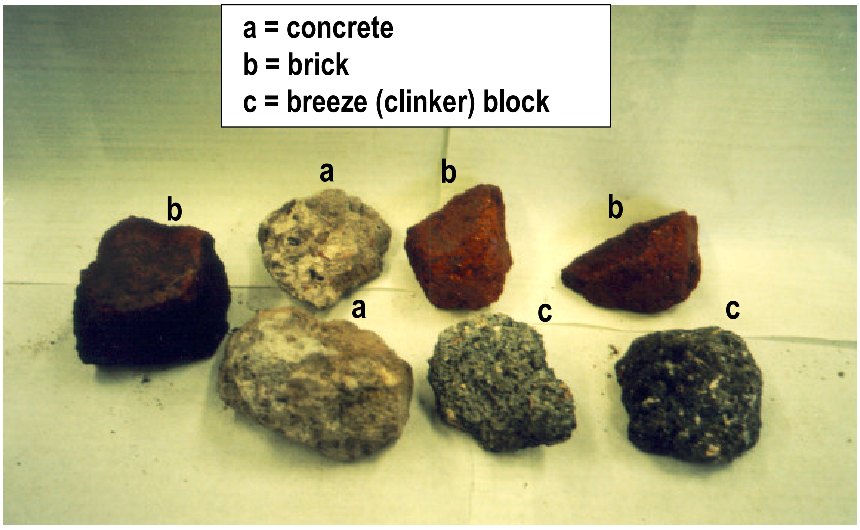


Figure 5.1: Typical ceramic-type Materials in Demolition Arisings

Figure 5.2: Typical contaminants in demolition arisings

Table 5.1: Summary of demolition arising samples

Sample code	Number of samples	Production process
75DP	20	Crushed demolition arising was produced in one pass through the jaw crusher with the discharge setting at 75 mm. Prior to crushing, finer material (less than 50 mm) was removed via the vibrating grizzly screen and re-introduced, upstream, onto the discharge conveyor with the crushed material.
50DP	20	Crushed demolition arising was produced in one pass through the jaw crusher with the discharge setting at 75 mm. Prior to crushing, finer material (less than 50 mm) was removed via the vibrating grizzly screen and re-introduced, upstream, onto the discharge conveyor with the crushed material. The material downstream of the discharge conveyor was subsequently passed through a single 50 mm screen.
75GP	20	Crushed demolition arising was produced in one pass through the jaw crusher with the discharge setting at 75 mm. Prior to crushing, finer material (less than 50 mm) was removed via the vibrating grizzly chute and discharged via the discharge dirt conveyor (i.e. the finer material was not re-introduced into the process).

5.2.2 Roadway arisings

The roadway arisings were obtained from Greendykes road, Dundee. The roadway structure was 100 mm of asphalt surfacing and 600 mm of stone setts, with concrete kerb along the sides. Hence, the material consisted of mainly crushed rock, concrete and bituminous mixes. The roadway arisings has been classified as a ceramic-polymeric-type material (section 4.3.4). Figure 5.3 shows typical ceramic-polymeric-type in the roadway arisings. The material was produced in one pass through the jaw crusher. Due to the source of the material, it was relatively free of “contaminants”.

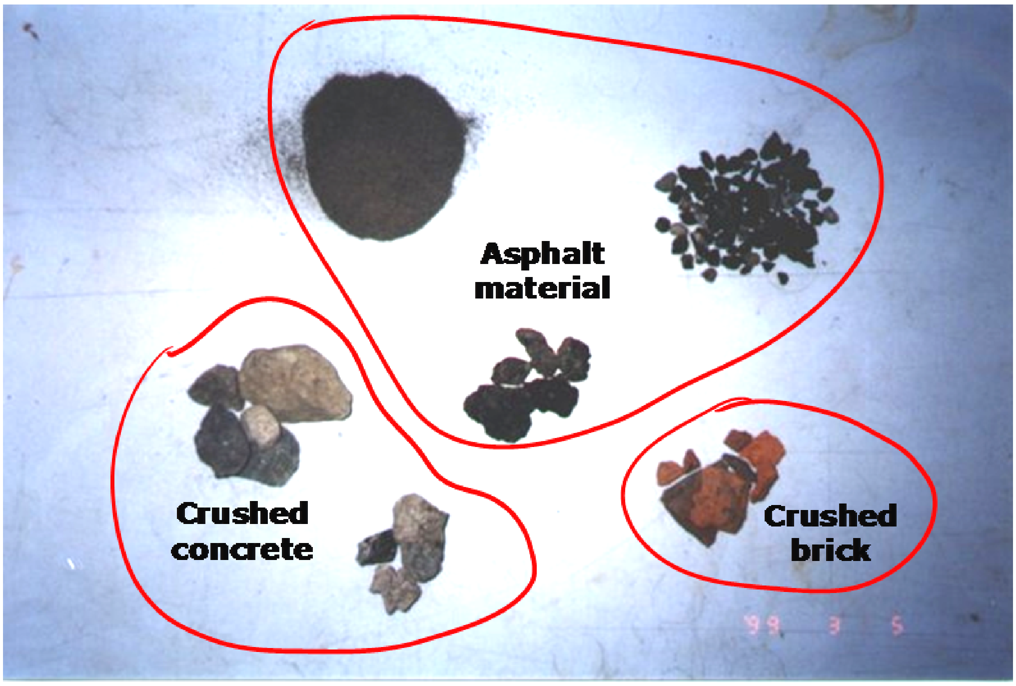


Figure 5.3: Typical ceramic-polymeric-type materials in roadway arisings

5.3 Grading of Demolition Arisings

One of the requirements for road pavements given in the specifications around the world is aggregate grading. The grading, with adequate compaction, gives an indication of stability, porosity, permeability, stiffness, and frost susceptibility of a material. For example, a coarser grading is indicative of a material with a higher permeability, lower frost susceptibility and possibly higher stiffness. A dense mixture may be obtained when the particle size distributions tend towards the theoretical distribution given by Fuller's power grading law (equation 3.4), and the particle distribution of many highway authorities follow this distribution (European Commission - DGVII 1999). If fines are excessive, the mixture may lack stability; if the fines content is low, the mixture will tend to be stony and porous, and usually require additional fines to obtain good stability. The addition of fines to a granular mixture at first increases density and strength as the interstices are filled, and then decreases density and strength as the fine grained material takes up a larger amount of space and prevents interlocking. Segregation may occur due to a lack of middle aggregate sizes. It is important to obtain the correct grading design for unbound (and bound) materials as previous research has shown that performance is dependent on grading (Brown and Chan 1996, Cabrera and Hamzah 1996, Thom and Brown 1988).

In view of the above, an extensive investigation was undertaken to assess the possibility of providing a range of grading from a supply of mixed crushed demolition arisings produced using a primary jaw crusher. Details of the work undertaken have been published by Ogwuda, et al. (1998), and is reproduced in Appendix C.

5.3.1 Materials Science Appraisal of Grading of Demolition Arisings

Figure 5.4, Figure 5.5 and Figure 5.6 show the average gradings of the demolition arisings alongside the grading of the Fuller curve, in the range 0.35 to 0.45, which gives the maximum contact points between aggregate particles (Arm 2003, Cooper 1994). Production of the demolition arisings and grading (linked to production) have the potential to be incorporated into the appraisal. The Fuller curve in the range n = 0.35 to 0.45 is the basis that has been used for the application of the materials science appraisal to the grading of the demolition arisings. Careful examination of the grading analysis has been undertaken, and what are considered to be key components in application of the appraisal have been identified and are presented in sections 5.3.1.1 to 5.3.1.6. This is based on the detailed methodology given in Chapter 4 (section 4.5.2); a summary of the methodology is shown as Figure 4.3.

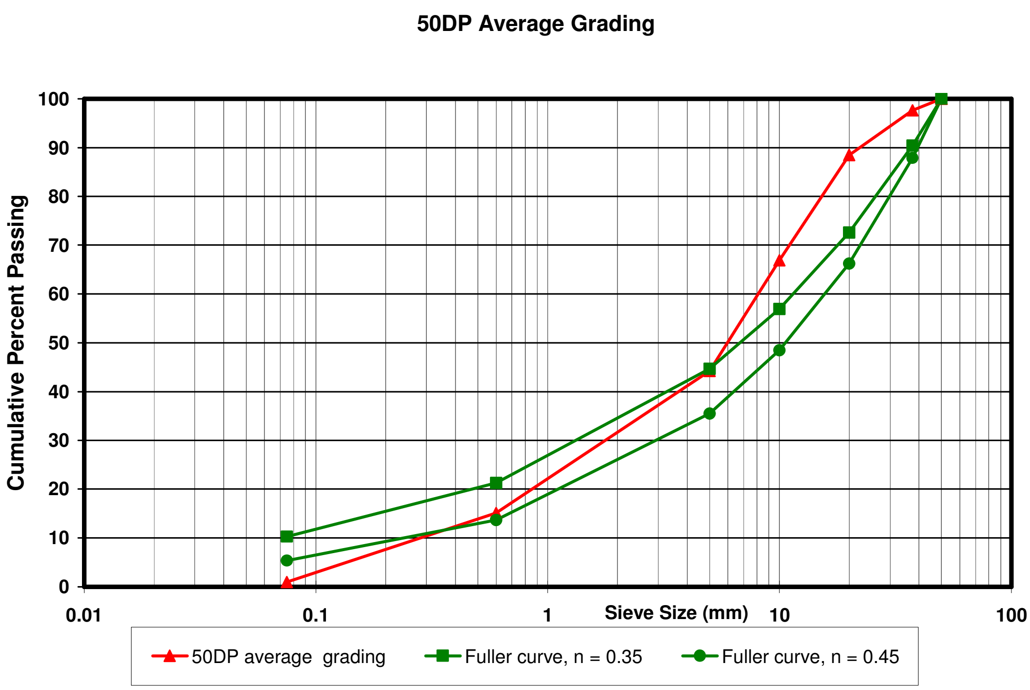


Figure 5.4: 50DP Average grading and Fuller curves (n = 0.35 and n = 0.45)

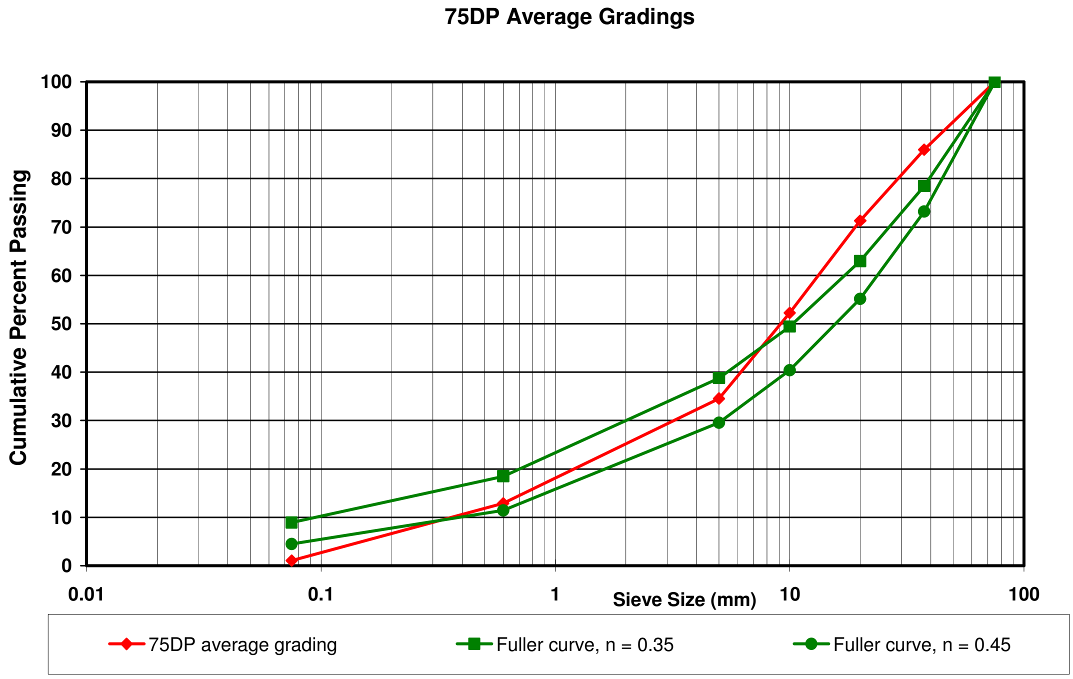


Figure 5.5: 75DP Average grading and Fuller curves (n = 0.35 and n = 0.45)

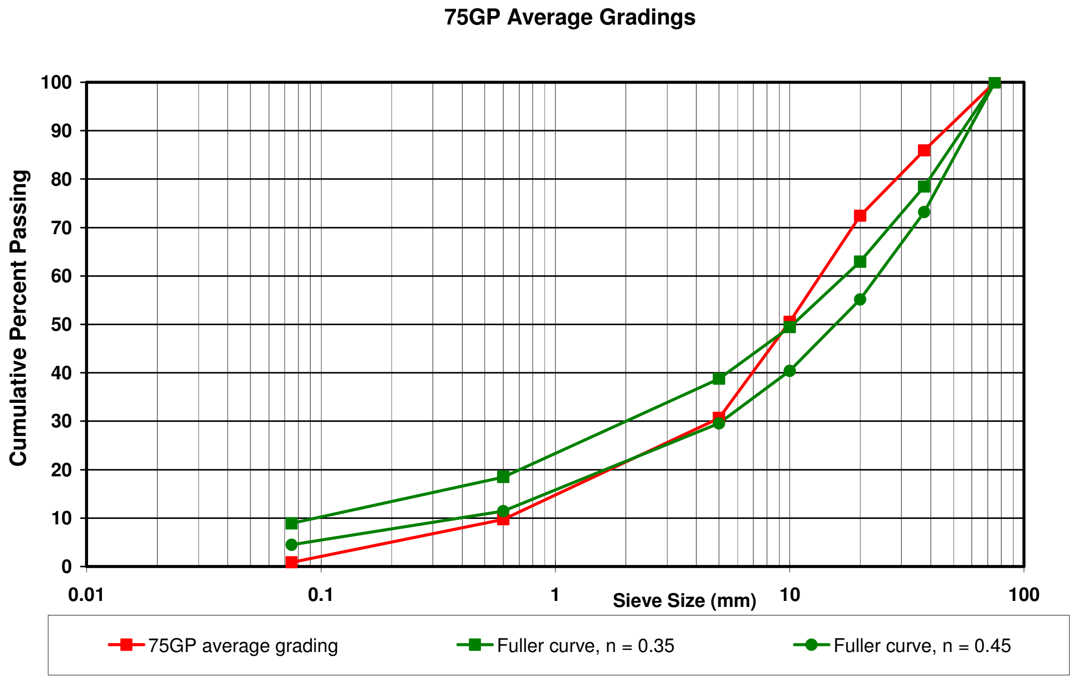


Figure 5.6: 75GP Average grading and Fuller Curves (n = 0.35 and n = 0.45)

5.3.1.1 Stage 1: Performance Requirements and Associated Dominant Pavement Distress

Grading based on the Fuller curve in the range 0.35 to 0.45 will give the maximum number of particle contact points. High density is one mitigating generic requirement (see Table 4.2) that may be considered to be directly related to the maximum number of particle contact points. High density is considered to reduce distortion, which is one of the main modes of pavement distress (see Table 4.2). Performance requirements that are associated and categorised with distortion include creep resistance, adequate density, low moisture movement, adequate stiffness, adequate strength, and low thermal movement (see Table 4.1). Note that high density is not the only mitigating generic requirement that will reduce distortion; the suite of mitigating generic requirements are listed in Table 4.2.

5.3.1.2 Stage 2: Mitigating Generic Requirements and Weighting

High density is one of the mitigating generic requirements considered to reduce distortion. Weightings are assigned to mitigating generic requirements, based on the hierarchical importance of generic requirements within a particular performance requirement, which will include product application. Since density is the only mitigating generic requirement under consideration within the performance requirement, the weighting assigned is 100 (i.e. at least one generic requirement should have a weighting of 100).

5.3.1.3 Stage 3: Material-type and Product Score

Material-type suitability is based on the material-type definitions given in sections 4.3.1 to 4.3.4. Product scores can have values of 1, 5, 7 or 10, with 10 being the more/most suitable material-type and 1 being of low suitability. Table 4.3 includes material-type suitability for the mitigating generic requirement of high density. From Table 4.3, and for the mitigating generic requirement of density, the demolition arisings are all ceramic-type materials, and are considered more suitable when compared to polymeric-type materials. Product scores assigned to high density are also based on the average grading of the demolition arising in relation to the Fuller curve, i.e. the range of the average grading curve that fits within the Fuller curves given in Figure 5.4, Figure 5.5 and Figure 5.6. Hence, the scores assigned to the

50DP, 75DP and 75GP samples of demolition arisings are 5, 7 and 1, respectively.

5.3.1.4 Stage 4: MS Number

The weighted scores for each product are shown in Table 5.2. The weighted score is calculated using equation 4.1. Once the weighted scores have been calculated the Materials Science (MS) number can be calculated. The MS number, which ranges from 1000 to 100000, is a weighted sum of the weighted scores of all generic requirements and is calculated using equation 4.2. The higher the MS number the higher the density; and the better road product. The MS number for the 50DP, 75DP and 75GP samples are also shown in Table 5.2. The MS numbers for the 50DP and 75GP samples are in the red zone while that for the MS number is in the yellow zone (see Figure 4.4).

Table 5.2: Weighted scores and MS number from grading analysis of demolition arisings

Stage 2		Stage 3			Stage 4		
Mitigating generic requirements	Generic requirement weighting	Product Score			Weighted Score		
		50DP	75DP	75GP	50DP	75DP	75GP
High density	100	5	7	1	2500	4900	100
				actual sum	2500	4900	100
				ideal sum	10000	10000	10000
				MS number	**25000**	**49000**	**1000**

5.3.1.5 Stage 5: Sensitivity Analysis

As only one generic requirement – high density – is being considered there is not a wide scope for a sensitivity analysis in relation to varying the product scores. In addition there is no scope for varying the weighting of the generic requirements as at least one generic requirement should have a weighting of 100. In changing the product score, the order of assigning the scores is similar to that used in section 5.3.1.3 (i.e. Stage 3), and is as follows (from highest to lowest): 75DP, 50DP and 75GP. Table 5.3 shows the effect of changing the product score on the MS number.

The most significant change occurs in the 75DP arisings where the MS number rises from 49000 to 100000, i.e. from yellow to green zone (see Figure 4.4). The 50DP and 75GP samples remain in the yellow and red zones, respectively. A rational approach with a degree of objectivity should be used in assigning and varying the product score. A judgement will also need to be made if a non ceramic-type material was being compared with the ceramic-type material (e.g. polymeric-type or ceramic-polymeric-type material).

Table 5.3: Sensitivity analysis of grading for demolition arisings

Stage 4 evaluation (section 5.3.1.4)

Stage 2		**Stage 3**			**Stage 4**		
Mitigating generic requirements	**Generic requirement weighting**	**Product Score**			**Weighted Score**		
		50DP	**75DP**	**75GP**	**50DP**	**75DP**	**75GP**
High density	100	5	7	1	2500	4900	100
				actual sum	2500	4900	100
				ideal sum	10000	10000	10000
				MS number	**25000**	**49000**	**1000**

Sensitivity analysis 1

Stage 2		**Stage 3**			**Stage 4**		
Mitigating generic requirements	**Generic requirement weighting**	**Product Score**			**Weighted Score**		
		50DP	**75DP**	**75GP**	**50DP**	**75DP**	**75GP**
High density	100	7	10	5	4900	10000	2500
				actual sum	4900	10000	2500
				ideal sum	10000	10000	10000
				MS number	**49000**	**100000**	**25000**

Table 5.3: Sensitivity analysis of grading for demolition arisings

Sensitivity analysis 2							
Stage 2		Stage 3			Stage 4		
Mitigating generic requirements	Generic requirement weighting	Product Score			Weighted Score		
		50DP	75DP	75GP	50DP	75DP	75GP
High density	100	5	10	1	2500	10000	100
				actual sum	2500	10000	100
				ideal sum	10000	10000	10000
				MS number	**25000**	**100000**	**1000**

5.3.1.6 Stage 6: Road Product Decision

The removal of fines during the production of the crushed demolition arising, i.e. going from a 75DP to 75GP demolition arising, should be carefully considered since this may have a crucial effect on grading. Jaw crushing operations on site can be adjusted to produce varied grading distributions to meet different requirements.

The performance requirements associated with high density are creep resistance, adequate density, low moisture movement, adequate stiffness, adequate strength, and low thermal movement (see Table 4.1); and the associated dominant form of pavement distress is distortion. An engineering decision could be that the 75DP demolition arisings would be the preferred product. However, consideration would need to be given to the other distortion mitigating generic requirements.

5.4 Plasticity of Demolition Arisings

Plasticity is an important feature of fine-grained construction materials, and the term plasticity describes the ability of the material to undergo unrecoverable deformation without cracking or crumbling. Plasticity in demolition arisings occurs due to the presence of clay minerals or organic material. For a soil to exist in the plastic state the net attractive forces between the particles must be of such magnitude that the particles are free to slide relative to each other, with cohesion between them being maintained (Craig 1997). This analogy can be extended to demolition arisings.

Plasticity tests were carried out on the samples of demolition arisings in accordance with British Standards (British Standards Institution 1990d). In essence the test involves mixing approximately 20 g of the material passing the 425 µm BS sieves with distilled water until it becomes sufficiently plastic to be moulded into a ball. An attempt was made to form part of the moulded ball (approximately 2.5 g) of the demolition arising into a thread of about 6 mm diameter and 50 mm length but the sample crumbled at each attempt. This observation is indicative of a fine-grained construction material (e.g. soil) that has lower plasticity. It is not uncommon for demolition arisings to be non-plastic even though there maybe up to 10% clay brick content in the arisings (O'Mahony 1990, Poon 1997).

5.4.1 Materials Science Appraisal of Plasticity of Demolition Arisings

Plasticity of the demolition arisings has the potential to be incorporated into the materials science appraisal. High plasticity is a mitigating generic requirement for fracture (Table 4.2), which is the basis that has been used for the application of the appraisal to the performance of the demolition arisings. Sections 5.4.1.1 to 5.4.1.6 give details of the application of the methodology.

5.4.1.1 Stage 1: Performance Requirements and Associated Dominant Pavement Distress

High plasticity is one mitigating generic requirement (see Table 4.2) is considered to reduce fracture, which is one of the main modes of pavement distress (see Table 4.2). Performance requirements that are associated and categorised with fracture include low brittleness, adequate elasticity, low fatigue, and adequate toughness (see Table 4.1). Note that high plasticity is not the only mitigating generic requirement that will reduce fracture; the suite of mitigating generic requirements are listed in Table 4.2.

5.4.1.2 Stage 2: Mitigating Generic Requirements and Weighting

High plasticity is one of the mitigating generic requirements considered to reduce distortion. Weightings are assigned to mitigating generic requirements, based on the hierarchical importance of generic requirements within a particular performance requirement, which will include product application. Since plasticity is the only mitigating generic requirement under consideration within the performance requirement, the weighting assigned is 100 (i.e. at least one generic requirement should have a weighting of 100).

5.4.1.3 Stage 3: Material-type and Product Score

Material-type suitability is based on the material-type definitions given in sections 4.3.1 to 4.3.4. Table 4.3 includes material-type suitability for the mitigating generic requirement of high plasticity. From Table 4.3, and for the mitigating generic requirement of high plasticity, the demolition arisings are all ceramic-type materials and are considered less suitable when compared to polymeric-type materials or metallic-type materials. The demolition arisings can be assigned a score of 1 or 5 or 7. If the arisings had a higher amount of clay bricks (relatively higher plasticity) then the score could be 7. Arisings with little or no clay bricks (e.g. concrete arisings) would be assigned a score of 1. A product score of 10 is not considered appropriate for the arisings.

5.4.1.4 Stage 4: MS Number

The weighted score is calculated using equation 4.1; calculated weighted scores for each product are shown in Table 5.4. The MS is calculated using equation 4.2. The calculated MS numbers for the non-plastic demolition arisings are also shown in Table 5.4.

Table 5.4: Weighted scores and MS number from plasticity analysis of demolition arisings (non-plastic)

Stage 2		Stage 3			Stage 4		
Mitigating generic requirements	**Generic requirement weighting**	**Product Score**			**Weighted Score**		
High plasticity (ductility)	100	1	5	7	100	2500	4900
				actual sum	100	2500	4900
				ideal sum	10000	10000	10000
				MS number	**1000**	**25000**	**49000**

5.4.1.5 Stage 5: Sensitivity Analysis

Like the sensitivity analysis for density (section 5.3.1), only one generic requirement – high plasticity – is being considered there; hence there is not a wide scope for a sensitivity analysis in relation to varying the product scores.

In addition there is no scope for varying the weighting of the generic requirements as at least one generic requirement should have a weighting of 100. The sensitivity analysis comes from varying the product score as shown in Table 5.4. The most significant change occurs where the MS number rises from 1000 to 49000 (red to green zone). A rational approach with a degree of objectivity should be used in assigning and varying the product score.

5.4.1.6 Stage 6: Road Product Decision

The performance requirements associated with high plasticity are low brittleness, adequate elasticity, low fatigue, and adequate toughness (see Table 4.1); and the associated dominant form of pavement distress is fracture. An engineering decision could be that the arisings would not be suitable based on these requirements. However, consideration would need to be given to the other fracture mitigating generic requirements.

5.5 Density-Moisture Content Relationship of Construction Arisings

Compaction tests were carried out using CBR moulds (2.3 litres) in accordance with British Standard procedures (British Standards Institution 1990e). The 1 litre (Proctor) mould was not used as it was considered that the maximum aggregate size from the grading of the demolition arisings would influence the compaction test. Before compaction began, the moisture content of all samples were determined in order to estimate the amount of water required to achieve a target moisture content for the compaction test. The sample was placed into a mixing bowl and, initially, approximately 2% of water was added.

For the CBR moulds particles retained on the 37.5 mm were removed and replaced by the same quantity of similar material passing the 37.5 mm sieve and retained on the 20 mm sieve. Arisings with sizes greater than 37.5 mm (up to 75 mm) do not show any significant difference in moisture-density relationships from arisings in which the sizes greater than 37.5 mm have been removed (O'Mahony and Milligan 1991). Compaction in the CBR moulds was undertaken using the vibrating hammer (demolition arisings) or 4.5 kg rammer (roadway arisings). With the vibrating hammer samples were compacted into the mould in three approximately equal layers, each layer being compacted for approximately 60 seconds with the vibratory hammer.

With the 4.5 kg rammer samples were compacted in five approximately equal layers. Samples were removed from the mould and a representative sample taken for moisture content determination. Test results of the relationships between dry density and moisture content are shown as Table 5.5.

Table 5.5: Density-moisture content relationship in CBR mould

Sample 1 (vibrating hammer – demolition arisings)					
Moisture Content (%)	9.39	9.87	12.05	13.16	15.35
Dry density (g/cm^3)	1.776	1.788	1.813	1.763	1.705

Sample 2 (vibrating hammer – demolition arisings)					
Moisture Content (%)	6.87	9.87	12.10	12.98	15.02
Dry density (g/cm^3)	1.747	1.830	1.766	1.730	1.649

Sample 3 (vibrating hammer – demolition arisings)					
Moisture Content (%)	9.43	9.89	12.08	13.36	16.26
Dry density (g/cm^3)	1.743	1.778	1.799	1.767	1.699

Sample 4 (4.5 kg rammer – roadway arisings)					
Moisture Content (%)	4.21	6.19	8.90	10.14	13.29
Dry density (g/cm^3)	2.010	2.057	2.057	1.982	1.912

Sample 5 (4.5 kg rammer – roadway arisings)					
Moisture Content (%)	3.84	4.44	8.39	10.90	10.28
Dry density (g/cm^3)	1.909	1.974	2.031	1.973	1.952

Sample 6 (4.5 kg rammer – roadway arisings)					
Moisture Content (%)	4.05	6.13	7.47	9.00	13.04
Dry density (g/cm^3)	2.001	2.022	2.023	2.009	1.906

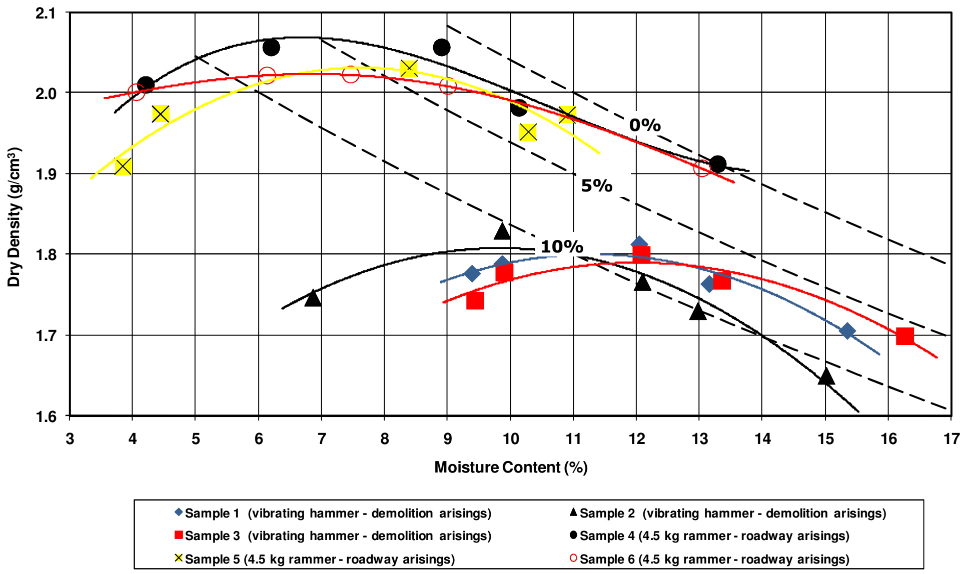


Figure 5.7: Density-moisture content relationship in CBR mould

Figure 5.7 shows that the maximum dry density (MDD) is at least 1.780 g/cm^3 while the optimum moisture content (OMC) ranges from about 7 to 12%. The vibratory method (demolition arisings) tends to give lower MDDs and higher OMCs compared to the 4.5 kg rammer method (roadway arisings). The values for MDD and OMC are characteristic of sandy soil (Croney and Croney 1997, Ingles and Metcalf 1972, Watson 1994). The OMC for the demolition arisings is higher than is usual for aggregates with similar grading, mainly due to the absorption of moisture by mortar and clinker blocks in the material. As may be expected, the roadway arisings gives relatively lower moisture content values. Overall the MDD tends to occur at 5 to 10% air voids, calculated from the aggregate specific gravity determined in accordance with British Standards (British Standards Institution 1995).

5.5.1 Materials Science Appraisal of Density-Moisture Content Relationship of Construction Arisings

Density-moisture content relationship of the demolition arisings has the potential to be incorporated into the material science appraisal. Density is one of the performance requirements given in Table 4.1, which is the basis that has been used for the application of the appraisal to the performance of the demolition arisings.

5.5.1.1 Stage 1: Performance Requirements and Associated Dominant Pavement Distress

Performance requirement for the road product application is density and the associated dominant pavement distress is distortion.

5.5.1.2 Stage 2: Mitigating Generic Requirements and Weighting

Mitigating generic requirements and weightings associated with distortion are shown in Table 5.6. Weightings have been assigned to mitigating generic requirements, based on the hierarchical importance of generic requirements within a particular performance requirement, which includes product application. At least one generic requirement (high density in this case) has been given a weighting of 100; otherwise the evaluation would be meaningless in terms of importance of performance requirement.

The proposed weighting values are chosen so that there will be distinct discriminating effects of the important (density) and non-important generic requirements (Low thermal movement and Low creep movement). The thinking behind the weightings that have been assigned is based on the use of the material as a sub-base, hence:

1. High density is considered to be most significant in relation to having adequate density; hence weighting of 100.
2. Maintenance of density can be achieved through high interparticle friction and high stiffness and high strength; hence weightings of 50.
3. Assuming a sealed surface with adequate drainage, movement in relation to moisture is not really an issue; hence the weightings of 1.
4. Low thermal movement and low creep are not considered to be issues at the sub-base level in the road pavement; hence weightings of 1 have been assigned.

5.5.1.3 Stage 3: Material-type and Product Score

Material-types that are more suitable for each generic requirement are shown in Table 5.6. The roadway arisings are considered to be ceramic-polymeric-type materials while the demolition arisings are ceramic-type materials.

For each generic requirement, product scores have been assigned to the road product (based on classification of road product and material-type suitability criteria). Better scores have been awarded to the demolition arisings, relative to the roadway arisings, for the mitigating generic requirements of high interparticle friction, high stiffness, high density and high strength. In this instance, the scores are 10 (higher score) against 7 (lower score), but could be 10 (higher score) against 5 (lower score) or 7 (higher score) against 5 (lower score). It is not considered that a score of 1 would be appropriate for the roadway arisings. Sensitivity analysis (stage 5) can evaluate the effect of variation of the product score.

The mitigating generic requirements of low thermal movement and low creep movement have been assigned the same product scores. For demolition arisings, better product scores have been assigned to low thermal movement and low creep movement in comparison to low moisture movement. The reason for this is that the demolition arisings are more suited for low thermal and creep movement in relation to low moisture movement. For the roadway arisings, the same product scores have been assigned to low thermal movement, low creep movement and low moisture movement. The roadway arisings are considered to have less moisture movement and, potentially, be superior to the demolition arisings in relation to moisture movement. Sensitivity analysis can test the variation of these scores – however, there is not likely to be any significant changes in the MS number as the weighting of these generic requirements are equal to 1.

5.5.1.4 Stage 4: Materials Science (MS) Number

The weighted score is calculated using equation 4.1, i.e. by multiplying the generic requirement weighting by the square of the road product score and the results are shown in Table 5.6. The MS number, which ranges from 1000 to 100000, is calculated using equation 4.2. The weighted scores for each generic requirement and the MS number for both arisings are shown in Table 5.6. The MS number for the demolition arisings is in the green zone (99704) while that for the roadway arisings is in the yellow zone (49000). The magnitude of the MS number is influenced by the generic requirement weightings of 50 and 100, and whichever product score has at least 10% presence in these weightings. A summary of how the MS number is influenced by the product scores at weightings of 50 and 100 was shown as Table 4.4.

5.5.1.5 Stage 5: Sensitivity Analysis

Table 5.7 shows the sensitivity analysis undertaken on the product score from Stage 3 (section 5.5.1.3).

1. **Sensitivity Analysis 1:** The roadway arisings product scores for mitigating generic requirements of high interparticle friction, high stiffness, high density and high strength have been reduced from 7 to 5 and, consequently, reduces the MS number from 49000 to 25285 (yellow to red zone). Table 5.7 reflects the effect of varying the product scores from 7 to 5.

2. **Sensitivity Analysis 2:** The demolition arisings product scores for mitigating generic requirements of high interparticle friction, high stiffness, high density and high strength have been reduced from 10 to 7 and, consequently, reduces the MS number from 99704 to 49308 (green to yellow zone). For the same generic requirements and considering that demolition arising product scores are to be higher than those of the roadway arisings, the corresponding scores for the roadway arisings have been reduced from 7 to 5, hence reducing the MS number from 49000 to 25285 (yellow to red zone). Table 5.7 reflects the effect of varying the product scores.

3. **Sensitivity Analysis 3:** In this analysis the product scores for mitigating generic requirements of low thermal movement and low creep movement have been reduced from 10 to 7 (demolition arisings) and 7 to 5 (roadway arisings), while the product score for low moisture movement has remained the same, at 7 (roadway arisings) and 5 (demolition arisings). Ceramic-type materials are more suited for low thermal and creep movement in relation to low moisture movement and thus the product score for low moisture movement has been kept at 5. However, since the roadway arisings is a ceramic-polymeric-type material the product score for low moisture movement has been kept at a relatively higher value of 7. The MS number is now reduced from 99704 to 99300 (changes within green zone) and 49308 to 48810 (changes within yellow zone) for the demolition arisings and roadway arisings, respectively. The change in MS number is relatively insignificant due to the weighting of the generic requirement. Table 5.7 shows the effect of the variation.

4. **Sensitivity Analysis 4:** In this analysis the product scores for mitigating generic requirements of low thermal movement and low creep movement have been reduced from 10 to 5 (demolition arisings) and 7 to 1 (roadway arisings). The product score for low moisture movement has been reduced from 7 to 5 (roadway arisings) and 5 to 1 (demolition arisings). The MS number is now reduced from 99704 to 99016 (changes within green zone) for the demolition arisings and 49000 to 48526 (changes within yellow zone) for the roadway arisings. The change in MS number is relatively insignificant due to the weighting of the generic requirement. Table 5.7 shows the effect of the variation.

5. **Sensitivity Analysis 5:** This combines the actions undertaken in sensitivity analyses 2 and 4. The mixed demolition arisings product scores for mitigating generic requirements of high interparticle friction, high stiffness, high density and high strength have been reduced from 10 to 7 and, considering that the scores for the demolition arisings are to be higher than those of the roadway arisings, the corresponding scores for the roadway arisings have been reduced from 7 to 5. Also, for both arisings, the product scores for mitigating generic requirements of low thermal movement and low creep movement have been reduced from 10 to 5 (demolition arisings) and 7 to 1 (roadway arisings). The product score for low moisture movement has reduced from 5 to 1. The product score for low moisture movement has been reduced from 7 to 5 (roadway arisings) and 5 to 1 (demolition arisings). The overall effect of this variation is to reduce the MS number from 99704 to 48621 (green to yellow zone) and 49000 to 24810 (yellow to red zone) for the demolition arisings and roadway arisings, respectively. These reductions are similar to that occurring with sensitivity analysis 2, which shows the effect that weighting has on the MS number. More significant changes in MS number occur with higher magnitudes (i.e. 50 and 100) of generic requirement weighting.

For other combinations of product score, Table 4.4 shows how the MS number is likely to vary.

Table 5.6: MS methodology applied to density-moisture content relationship for demolition arisings

Stage 1		Stage 2		Stage 3				Stage 4	
Performance requirement	Dominant pavement distress	Mitigating generic requirements	Generic requirement weighting	Material more suited	Material less suited	Product score		Weighted score	
						roadway arisings	demolition arisings	roadway arisings	demolition arisings
Adequate Density	Distortion	High interparticle friction	50	ceramic-type	metallic-type polymeric-type	7	10	2450	5000
Adequate Density	Distortion	High stiffness	50	ceramic-type metallic-type	polymeric-type	7	10	2450	5000
Adequate Density	Distortion	High density	100	ceramic-type metallic-type	polymeric-type	7	10	4900	10000
Adequate Density	Distortion	Low moisture movement	1	metallic-type polymeric-type	ceramic-type	7	5	49	25
Adequate Density	Distortion	Low thermal movement	1	ceramic-type metallic-type	polymeric-type	7	10	49	100
Adequate Density	Distortion	Low creep movement	1	ceramic-type	metallic-type polymeric-type	7	10	49	100
Adequate Density	Distortion	High strength	50	ceramic-type metallic-type	polymeric-type	7	10	2450	5000
							actual sum	12397	25225
							ideal sum	25300	25300
							MS number	**49000**	**99704**

Table 5.7: Sensitivity analysis of density-moisture content relationship for demolition arisings

Sensitivity analysis 1

Stage 1		Stage 2		Stage 3				Stage 4	
Performance requirement	**Dominant pavement distress**	**Mitigating generic requirements**	**Generic requirement weighting**	**Material more suited**	**Material less suited**	**Product score**		**Weighted score**	
						roadway arisings	**demolition arisings**	**roadway arisings**	**demolition arisings**
Adequate Density	Distortion	High interparticle friction	50	ceramic-type	metallic-type polymeric-type	5	10	1250	5000
Adequate Density	Distortion	High stiffness	50	ceramic-type metallic-type	polymeric-type	5	10	1250	5000
Adequate Density	Distortion	High density	100	ceramic-type metallic-type	polymeric-type	5	10	2500	10000
Adequate Density	Distortion	Low moisture movement	1	metallic-type polymeric-type	ceramic-type	7	5	49	25
Adequate Density	Distortion	Low thermal movement	1	ceramic-type metallic-type	polymeric-type	7	10	49	100
Adequate Density	Distortion	Low creep movement	1	ceramic-type	metallic-type polymeric-type	7	10	49	100
Adequate Density	Distortion	High strength	50	ceramic-type metallic-type	polymeric-type	5	10	1250	5000
							actual sum	6349	25225
							ideal sum	25300	25300
							MS number	**25285**	**99704**

Table 5.7: Sensitivity analysis of density-moisture content relationship for demolition arisings

Sensitivity analysis 2									
Stage 1		**Stage 2**		**Stage 3**				**Stage 4**	
Performance requirement	**Dominant pavement distress**	**Mitigating generic requirements**	**Generic requirement weighting**	**Material more suited**	**Material less suited**	**Product score**		**Weighted score**	
						roadway arisings	**demolition arisings**	**roadway arisings**	**demolition arisings**
Adequate Density	Distortion	High interparticle friction	50	ceramic-type	metallic-type polymeric-type	5	7	1250	2450
Adequate Density	Distortion	High stiffness	50	ceramic-type metallic-type	polymeric-type	5	7	1250	2450
Adequate Density	Distortion	High density	100	ceramic-type metallic-type	polymeric-type	5	7	2500	4900
Adequate Density	Distortion	Low moisture movement	1	metallic-type polymeric-type	ceramic-type	7	5	49	25
Adequate Density	Distortion	Low thermal movement	1	ceramic-type metallic-type	polymeric-type	7	10	49	100
Adequate Density	Distortion	Low creep movement	1	ceramic-type	metallic-type polymeric-type	7	10	49	100
Adequate Density	Distortion	High strength	50	ceramic-type metallic-type	polymeric-type	5	7	1250	2450
							actual sum	6397	12475
							ideal sum	25300	25300
							MS number	**25095**	**49308**

Table 5.7: Sensitivity analysis of density-moisture content relationship for demolition arisings

Sensitivity analysis 3									
Stage 1		**Stage 2**		**Stage 3**				**Stage 4**	
Performance requirement	**Dominant pavement distress**	**Mitigating generic requirements**	**Generic requirement weighting**	**Material more suited**	**Material less suited**	**Product score**		**Weighted score**	
						roadway arisings	**demolition arisings**	**roadway arisings**	**demolition arisings**
Adequate Density	Distortion	High interparticle friction	50	ceramic-type	metallic-type polymeric-type	7	10	2450	5000
Adequate Density	Distortion	High stiffness	50	ceramic-type metallic-type	polymeric-type	7	10	2450	5000
Adequate Density	Distortion	High density	100	ceramic-type metallic-type	polymeric-type	7	10	4900	10000
Adequate Density	Distortion	Low moisture movement	1	metallic-type polymeric-type	ceramic-type	7	5	49	25
Adequate Density	Distortion	Low thermal movement	1	ceramic-type metallic-type	polymeric-type	5	7	25	49
Adequate Density	Distortion	Low creep movement	1	ceramic-type	metallic-type polymeric-type	5	7	25	49
Adequate Density	Distortion	High strength	50	ceramic-type metallic-type	polymeric-type	7	10	2450	5000
							actual sum	12349	25123
							ideal sum	25300	25300
							MS number	**48810**	**99300**

Table 5.7: Sensitivity analysis of density-moisture content relationship for demolition arisings

Sensitivity analysis 4									
Stage 1		**Stage 2**		**Stage 3**				**Stage 4**	
Performance requirement	**Dominant pavement distress**	**Mitigating generic requirements**	**Generic requirement weighting**	**Material more suited**	**Material less suited**	**Product score**		**Weighted score**	
						roadway arisings	**demolition arisings**	**roadway arisings**	**demolition arisings**
Adequate Density	Distortion	High interparticle friction	50	ceramic-type	metallic-type polymeric-type	7	10	2450	5000
Adequate Density	Distortion	High stiffness	50	ceramic-type metallic-type	polymeric-type	7	10	2450	5000
Adequate Density	Distortion	High density	100	ceramic-type metallic-type	polymeric-type	7	10	4900	10000
Adequate Density	Distortion	Low moisture movement	1	metallic-type polymeric-type	ceramic-type	5	1	25	1
Adequate Density	Distortion	Low thermal movement	1	ceramic-type metallic-type	polymeric-type	1	5	1	25
Adequate Density	Distortion	Low creep movement	1	ceramic-type	metallic-type polymeric-type	1	5	1	25
Adequate Density	Distortion	High strength	50	ceramic-type metallic-type	polymeric-type	7	10	2450	5000
							actual sum	12277	25051
							ideal sum	25300	25300
							MS number	**48526**	**99016**

Table 5.7: Sensitivity analysis of density-moisture content relationship for demolition arisings

Sensitivity analysis 5									
Stage 1		**Stage 2**		**Stage 3**				**Stage 4**	
Performance requirement	**Dominant pavement distress**	**Mitigating generic requirements**	**Generic requirement weighting**	**Material more suited**	**Material less suited**	**Product score**		**Weighted score**	
						roadway arisings	**demolition arisings**	**roadway arisings**	**demolition arisings**
Adequate Density	Distortion	High interparticle friction	50	ceramic-type	metallic-type polymeric-type	5	7	1250	2450
Adequate Density	Distortion	High stiffness	50	ceramic-type metallic-type	polymeric-type	5	7	1250	2450
Adequate Density	Distortion	High density	100	ceramic-type metallic-type	polymeric-type	5	7	2500	4900
Adequate Density	Distortion	Low moisture movement	1	metallic-type polymeric-type	ceramic-type	7	5	25	1
Adequate Density	Distortion	Low thermal movement	1	ceramic-type metallic-type	polymeric-type	5	10	1	25
Adequate Density	Distortion	Low creep movement	1	ceramic-type	metallic-type polymeric-type	5	10	1	25
Adequate Density	Distortion	High strength	50	ceramic-type metallic-type	polymeric-type	5	7	1250	2450
							actual sum	6277	12301
							ideal sum	25300	25300
							MS number	**24810**	**48621**

5.5.1.6 Stage 6: Road Product Decision

Performance requirement for the road product application is density and from the sensitivity analysis an engineering decision would be to opt for the demolition arisings as the preferred road product. In certain circumstances (see Table 5.7) the sensitivity analysis shows that the demolition arisings is significantly superior to the roadway arisings.

5.6 California Bearing Ratio (CBR)

The CBR test was conducted on samples at their OMC and maximum dry density and in accordance with British Standards (British Standards Institution 1990e). The values used for OMC and corresponding maximum dry density were obtained from previous compaction tests (section 5.5). Figure 5.8 shows the CBR plots of test results. Figure 5.8 shows that the demolition arisings have relatively higher load penetration resistance compared to the roadway arisings.

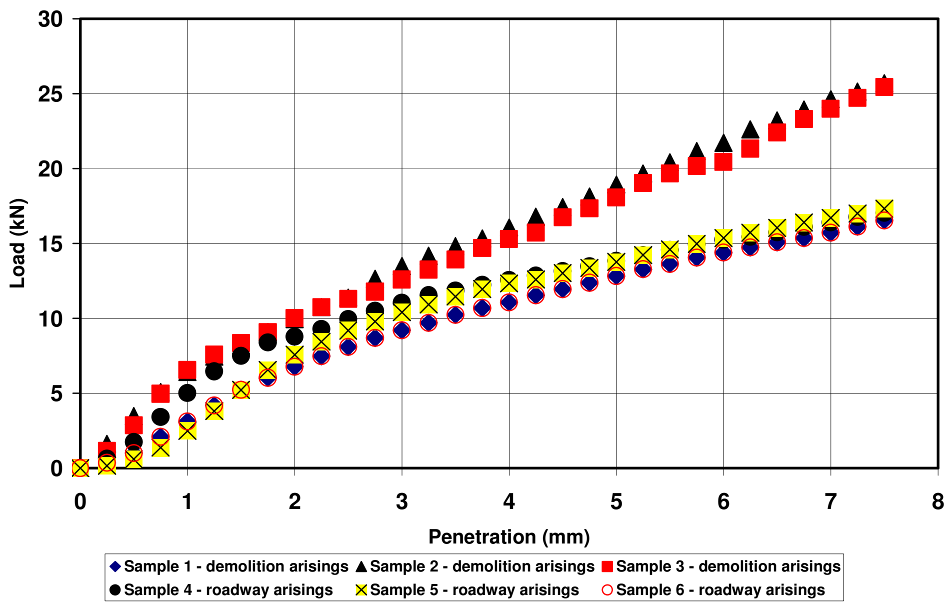


Figure 5.8: CBR plots

$$\text{CBR}\ (\%) = \frac{100 \times L_1}{13.24} \text{ or } \frac{100 \times L_2}{19.96} \qquad 4.3$$
$$\text{(whichever is greater)}$$

Where:

L_1 = Load applied (kN) on the sample at a penetration of 2.5 mm

L_2 = Load applied (kN) on the sample at a penetration of 5 mm

(L_1 and L_2 are considered at penetrations higher than 2.5 mm and 5 mm, respectively, if the initial part of the curve is concave upwards – details are given in Appendix B).

The CBR is calculated using equation 4.3, and the results are shown as Table 5.8 (details are given in Appendix B). Table 5.8 shows that the demolition arisings tend to give higher values that the roadway arisings.

Table 5.8: CBR calculations

Sample description	CBR (%)	average CBR (%)
Sample 1 - demolition arisings	70	
Sample 2 - demolition arisings	95	
Sample 3 - demolition arisings	91	85
Sample 4 - roadway arisings	75	
Sample 5 - roadway arisings	79	
Sample 6 - roadway arisings	64	73

5.6.1 Materials Science Appraisal of CBR of Construction Arisings

Strength is one of the performance requirements given in Table 4.1 and CBR is a measure of shear strength. Hence, strength is the basis that has been used for the appraisal of the performance of construction arisings.

5.6.1.1 Stage 1: Performance Requirements and Associated Dominant Pavement Distress

Performance requirement for the road product application is strength and the associated dominant pavement distress is distortion.

5.6.1.2 Stage 2: Mitigating Generic Requirements and Weighting

Mitigating generic requirements and weightings associated with distortion are shown in Table 5.9. Weightings have been assigned to mitigating generic requirements, based on the hierarchical importance of generic requirements within the performance requirement of CBR (strength). The thinking behind the weightings that have been assigned is based on the use of the material as a sub-base, hence:

1. High interparticle friction, high density and high strength are considered to be most significant in relation to having adequate strength; hence weighting of 100
2. Assuming a sealed surface with adequate drainage, movement in relation to moisture is not really an issue; hence the weightings of 1.
3. Low thermal movement and low creep are not considered to be issues at the sub-base level in the road pavement; hence weightings of 1 have been assigned.

5.6.1.3 Stage 3: Material-type and Product Score

Material-types that are more suitable for each generic requirement are shown in Table 5.9. The roadway arisings are considered to be ceramic-polymeric-type materials while the demolition arisings are ceramic-type materials.

For each generic requirement, product scores have been assigned to the road product (based on classification of road product and material-type suitability criteria). Better scores have been awarded to the demolition arisings, relative to the roadway arisings, for the mitigating generic requirements of high interparticle friction, high stiffness, high density and high strength. In this instance, the scores are 10 (higher score) against 7 (lower score), but could be 10 (higher score) against 5 (lower score) or 7 (higher score) against 5 (lower score). It is not considered that a score of 1 would be appropriate for the roadway arisings. Sensitivity analysis (stage 5) can evaluate the effect of variation of the product score.

The mitigating generic requirements of low thermal movement and low creep movement have been assigned the same product scores. For demolition arisings, better product scores have been assigned to low thermal movement and low creep movement in comparison to low moisture movement. The reason for this is that the demolition arisings are more suited for low thermal and creep movement in relation to low moisture movement. For the roadway arisings, the same product scores have been assigned to low thermal movement, low creep movement and low moisture movement. The roadway arisings are considered to have less moisture movement and, potentially, be superior to the demolition arisings in relation to moisture movement. Sensitivity analysis can test the variation of these scores – however, there is not likely to be any significant changes in the MS number as the weighting of these generic requirements are equal to 1.

5.6.1.4 Stage 4: Materials Science (MS) Number

The weighted score is calculated using equation 4.1, i.e. by multiplying the generic requirement weighting by the square of the road product score and the results are shown in Table 5.9. The MS number, which ranges from 1000 to 100000, is calculated using equation 4.2. The weighted scores for each generic requirement and the MS number for both arisings are shown in Table 5.9. The MS number for the demolition arisings is in the green zone (99788) while that for the roadway arisings is in the yellow zone (49000). The magnitude of the MS number is influenced by the generic requirement weightings of 50 and 100, and whichever product score has at least 10% presence in these weightings. A summary of how the MS number is influenced by the product scores at weightings of 50 and 100 was shown as Table 4.4.

5.6.1.5 Stage 5: Sensitivity Analysis

Table 5.10 shows the sensitivity analysis undertaken on the product score from Stage 3 (section 5.5.1.3).

1. **Sensitivity Analysis 1:** The roadway arisings product scores for mitigating generic requirements of high interparticle friction, high stiffness, high density and high strength have been reduced from 7 to 5 and, consequently, reduces the MS number from 49000 to 25204 (yellow to red zone). Table 5.10 reflects the effect of varying the product scores from 7 to 5.
2. **Sensitivity Analysis 2:** The demolition arisings product scores for mitigating generic requirements of high interparticle friction, high stiffness,

high density and high strength have been reduced from 10 to 7 and, consequently, reduces the MS number from 99788 to 49221 (green to yellow zone). For the same generic requirements and considering that demolition arising product scores are to be higher than those of the roadway arisings, the corresponding scores for the roadway arisings have been reduced from 7 to 5, hence reducing the MS number from 49000 to 25204 (yellow to red zone). Table 5.10 reflects the effect of varying the product scores.

3. **Sensitivity Analysis 3:** In this analysis the product scores for mitigating generic requirements of low thermal movement and low creep movement have been reduced from 10 to 7 (demolition arisings) and 7 to 5 (roadway arisings), while the product score for low moisture movement has remained the same, at 7 (roadway arisings) and 5 (demolition arisings). Ceramic-type materials are more suited for low thermal and creep movement in relation to low moisture movement and thus the product score for low moisture movement has been kept at 5. However, since the roadway arisings is a ceramic-polymeric-type material the product score for low moisture movement has been kept at a relatively higher value of 7. The MS number is now reduced from 99788 to 99499 (changes within green zone) and 49000 to 48864 (changes within yellow zone) for the demolition arisings and roadway arisings, respectively. The change in MS number is relatively insignificant due to the weighting of the generic requirement. Table 5.10 shows the effect of the variation.

4. **Sensitivity Analysis 4:** In this analysis the product scores for mitigating generic requirements of low thermal movement and low creep movement have been reduced from 10 to 5 (demolition arisings) and 7 to 1 (roadway arisings). The product score for low moisture movement has been reduced from 7 to 5 (roadway arisings) and 5 to 1 (demolition arisings). The MS number is now reduced from 99788 to 99295 (changes within green zone) for the demolition arisings and 49000 to 48660 (changes within yellow zone) for the roadway arisings. The change in MS number is relatively insignificant due to the weighting of the generic requirement. Table 5.10 shows the effect of the variation.

5. **Sensitivity Analysis 5:** This combines the actions undertaken in sensitivity analyses 2 and 4. The mixed demolition arisings product scores for mitigating generic requirements of high interparticle friction, high

stiffness, high density and high strength have been reduced from 10 to 7 and, considering that the scores for the demolition arisings are to be higher than those of the roadway arisings, the corresponding scores for the roadway arisings have been reduced from 7 to 5. Also, for both arisings, the product scores for mitigating generic requirements of low thermal movement and low creep movement have been reduced from 10 to 5 (demolition arisings) and 7 to 1 (roadway arisings). The product score for low moisture movement has reduced from 5 to 1. The product score for low moisture movement has been reduced from 7 to 5 (roadway arisings) and 5 to 1 (demolition arisings). The overall effect of this variation is to reduce the MS number from 99788 to 48728 (green to yellow zone) and 49000 to 24864 (yellow to red zone) for the demolition arisings and roadway arisings, respectively (see Table 5.10). These reductions are similar to that occurring with sensitivity analysis 2, which shows the effect that weighting has on the MS number. More significant changes in MS number occur with higher magnitudes (i.e. 50 and 100) of generic requirement weighting.

For other combinations of product score, Table 4.4 shows how the MS number is likely to vary.

Table 5.9: Materials science appraisal of CBR of construction arisings

Stage 1		Stage 2		Stage 3				Stage 4	
Performance requirement	Dominant pavement distress	Mitigating generic requirements	Generic requirement weighting	Material more suited	Material less suited	Product score		Weighted score	
						roadway arisings	demolition arisings	roadway arisings	demolition arisings
CBR (strength)	Distortion	High interparticle friction	100	ceramic-type	metallic-type polymeric-type	7	10	4900	10000
CBR (strength)	Distortion	High stiffness	50	ceramic-type metallic-type	polymeric-type	7	10	2450	5000
CBR (strength)	Distortion	High density	100	ceramic-type metallic-type	polymeric-type	7	10	4900	10000
CBR (strength)	Distortion	Low moisture movement	1	metallic-type polymeric-type	ceramic-type	7	5	49	25
CBR (strength)	Distortion	Low thermal movement	1	ceramic-type metallic-type	polymeric-type	7	10	49	100
CBR (strength)	Distortion	Low creep movement	1	ceramic-type	metallic-type polymeric-type	7	10	49	100
CBR (strength)	Distortion	High strength	100	ceramic-type metallic-type	polymeric-type	7	10	4900	10000
							actual sum	17297	35225
							ideal sum	35300	35300
							MS number	**49000**	**99788**

Table 5.10: Sensitivity analysis of CBR of construction arisings

Sensitivity analysis 1									
Stage 1		**Stage 2**		**Stage 3**				**Stage 4**	
Performance requirement	**Dominant pavement distress**	**Mitigating generic requirements**	**Generic requirement weighting**	**Material more suited**	**Material less suited**	**Product score**		**Weighted score**	
						roadway arisings	**demolition arisings**	**roadway arisings**	**demolition arisings**
Adequate Density	Distortion	High interparticle friction	100	ceramic-type	metallic-type polymeric-type	5	10	2500	10000
Adequate Density	Distortion	High stiffness	50	ceramic-type metallic-type	polymeric-type	5	10	1250	5000
Adequate Density	Distortion	High density	100	ceramic-type metallic-type	polymeric-type	5	10	2500	10000
Adequate Density	Distortion	Low moisture movement	1	metallic-type polymeric-type	ceramic-type	7	5	49	25
Adequate Density	Distortion	Low thermal movement	1	ceramic-type metallic-type	polymeric-type	7	10	49	100
Adequate Density	Distortion	Low creep movement	1	ceramic-type	metallic-type polymeric-type	7	10	49	100
Adequate Density	Distortion	High strength	100	ceramic-type metallic-type	polymeric-type	5	10	2500	10000
							actual sum	8897	35225
							ideal sum	35300	35300
							MS number	**25204**	**99788**

Table 5.10: Sensitivity analysis of CBR of construction arisings

Sensitivity analysis 2									
Stage 1		**Stage 2**		**Stage 3**				**Stage 4**	
Performance requirement	**Dominant pavement distress**	**Mitigating generic requirements**	**Generic requirement weighting**	**Material more suited**	**Material less suited**	**Product score**		**Weighted score**	
						roadway arisings	**demolition arisings**	**roadway arisings**	**demolition arisings**
Adequate Density	Distortion	High interparticle friction	100	ceramic-type	metallic-type polymeric-type	5	7	2500	4900
Adequate Density	Distortion	High stiffness	50	ceramic-type metallic-type	polymeric-type	5	7	1250	2450
Adequate Density	Distortion	High density	100	ceramic-type metallic-type	polymeric-type	5	7	2500	4900
Adequate Density	Distortion	Low moisture movement	1	metallic-type polymeric-type	ceramic-type	7	5	49	25
Adequate Density	Distortion	Low thermal movement	1	ceramic-type metallic-type	polymeric-type	7	10	49	100
Adequate Density	Distortion	Low creep movement	1	ceramic-type	metallic-type polymeric-type	7	10	49	100
Adequate Density	Distortion	High strength	100	ceramic-type metallic-type	polymeric-type	5	7	2500	4900
							actual sum	8897	17375
							ideal sum	35300	35300
							MS number	**25204**	**49221**

Table 5.10: Sensitivity analysis of CBR of construction arisings

Sensitivity analysis 3									
Stage 1		**Stage 2**		**Stage 3**				**Stage 4**	
Performance requirement	**Dominant pavement distress**	**Mitigating generic requirements**	**Generic requirement weighting**	**Material more suited**	**Material less suited**	**Product score**		**Weighted score**	
						roadway arisings	**demolition arisings**	**roadway arisings**	**demolition arisings**
Adequate Density	Distortion	High interparticle friction	100	ceramic-type	metallic-type polymeric-type	7	10	4900	10000
Adequate Density	Distortion	High stiffness	50	ceramic-type metallic-type	polymeric-type	7	10	2450	5000
Adequate Density	Distortion	High density	100	ceramic-type metallic-type	polymeric-type	7	10	4900	10000
Adequate Density	Distortion	Low moisture movement	1	metallic-type polymeric-type	ceramic-type	7	5	49	25
Adequate Density	Distortion	Low thermal movement	1	ceramic-type metallic-type	polymeric-type	5	7	25	49
Adequate Density	Distortion	Low creep movement	1	ceramic-type	metallic-type polymeric-type	5	7	25	49
Adequate Density	Distortion	High strength	100	ceramic-type metallic-type	polymeric-type	7	10	4900	10000
							actual sum	17249	35123
							ideal sum	35300	35300
							MS number	**48864**	**99499**

Table 5.10: Sensitivity analysis of CBR of construction arisings

Sensitivity analysis 4									
Stage 1		**Stage 2**		**Stage 3**				**Stage 4**	
Performance requirement	**Dominant pavement distress**	**Mitigating generic requirements**	**Generic requirement weighting**	**Material more suited**	**Material less suited**	**Product score**		**Weighted score**	
						roadway arisings	**demolition arisings**	**roadway arisings**	**demolition arisings**
Adequate Density	Distortion	High interparticle friction	100	ceramic-type	metallic-type polymeric-type	7	10	4900	10000
Adequate Density	Distortion	High stiffness	50	ceramic-type metallic-type	polymeric-type	7	10	2450	5000
Adequate Density	Distortion	High density	100	ceramic-type metallic-type	polymeric-type	7	10	4900	10000
Adequate Density	Distortion	Low moisture movement	1	metallic-type polymeric-type	ceramic-type	5	1	25	1
Adequate Density	Distortion	Low thermal movement	1	ceramic-type metallic-type	polymeric-type	1	5	1	25
Adequate Density	Distortion	Low creep movement	1	ceramic-type	metallic-type polymeric-type	1	5	1	25
Adequate Density	Distortion	High strength	100	ceramic-type metallic-type	polymeric-type	7	10	4900	10000
							actual sum	17177	35051
							ideal sum	35300	35300
							MS number	**48660**	**99295**

Table 5.10: Sensitivity analysis of CBR of construction arisings

Sensitivity analysis 5									
Stage 1		Stage 2		Stage 3				Stage 4	
Performance requirement	Dominant pavement distress	Mitigating generic requirements	Generic requirement weighting	Material more suited	Material less suited	Product score		Weighted score	
						roadway arisings	demolition arisings	roadway arisings	demolition arisings
Adequate Density	Distortion	High interparticle friction	100	ceramic-type	metallic-type polymeric-type	5	7	2500	4900
Adequate Density	Distortion	High stiffness	50	ceramic-type metallic-type	polymeric-type	5	7	1250	2450
Adequate Density	Distortion	High density	100	ceramic-type metallic-type	polymeric-type	5	7	2500	4900
Adequate Density	Distortion	Low moisture movement	1	metallic-type polymeric-type	ceramic-type	5	1	25	1
Adequate Density	Distortion	Low thermal movement	1	ceramic-type metallic-type	polymeric-type	1	5	1	25
Adequate Density	Distortion	Low creep movement	1	ceramic-type	metallic-type polymeric-type	1	5	1	25
Adequate Density	Distortion	High strength	100	ceramic-type metallic-type	polymeric-type	5	7	2500	4900
							actual sum	8777	17201
							ideal sum	35300	35300
							MS number	**24864**	**48728**

5.6.1.6 Stage 6: Road Product Decision

Performance requirement for the road product application is CBR and from the sensitivity analysis an engineering decision would be to opt for the demolition arisings as the preferred road product. In certain circumstances (see Table 5.10) the sensitivity analysis shows that the demolition arisings is significantly superior to the roadway arisings.

5.7 Summary

This chapter has demonstrated how the innovative materials science appraisal can be used in the evaluation of construction arisings; based on macroscopic materials science. The appraisal allows sensitivity analysis to be undertaken and informed engineering decisions on product choice to be made. The evaluation does not preclude a specific material, as it based on materials science, not material source.

Chapter 6 Integrated Evaluation of Materials Science Appraisal

6.1 Introduction

Choices made today will influence future sustainability, and the materials science appraisal attempts to provide a pathway for making informed decisions in sustainable road construction and maintenance.

The purpose of the materials science appraisal is to identify the performance requirements (road construction and maintenance), develop specific materials science criteria that will meet the requirements, and evaluate the road products relative to the criteria. The appraisal is a systematic procedure for making engineering decisions in road products, based on materials science and sensitivity analysis.

The sensitivity analysis process proposed by the appraisal aims to avoid getting involved in too much detail and to avoid missing relevant detail. Some materials science criteria are highly important and some are insignificant – hence the assigning of weightings.

It is recognised that the appraisal is part of a series of stages involved in the development of materials technology, as highlighted in section 3.6.

The appraisal covers materials science and engineering decision-making in relation to roadways. It does not, directly, include economic and environmental management issues.

6.2 Sensitivity Testing

The data that is input into the materials science appraisal is seldom known with complete certainty. A sensitivity analysis allows the effect of incremental changes to the requirement weighting and product score to be gauged; and hence assist in the engineering decision-making process. The requirement weightings are of particular interest within a sensitivity analysis as their valuation can be the result of “specialist” judgement – and specialists may have a difference of opinions as to the correct value. With product scores, sensitivity testing arises from errors that may derive from the actual estimation of the valuations themselves. They may be based on incomplete data or may be derived from judgements by specialists from the relevant field. Incremental changes in the product score possessing a high requirement weighting are more likely to alter the MS number than changes in the scores of less significant weighting. Particular attention might also be paid to product scores that involve a high degree of uncertainty and subjectivity. Competency should involve identifying such product scores and analysing the effect of their variation on the MS number.

6.3 Capability of Materials Science Appraisal

The materials science appraisal is simplistic and subjective in nature, which overcomes the illusion of precision that complex analysis may portray. Due to the simplicity the principle can be easily explained to decision-makers. The transparent and iterative way of arriving at the elements helps to build up confidence in the method, which can sometimes be eroded by the application of obscure statistical techniques. The transparency is good for dealing explicitly with balancing issues and compromises. The appraisal can handle complex analyses without losing its essential transparency.

Threshold values of MS numbers in relation to red, yellow and green zones gives an indication of the materials science performance nature of the road product and assists in engineering decision-making.

The power of the appraisal lies in the ability to make productive use of information and judgements. It provides a systematic framework for engineering decision-making for road products for use in road construction and maintenance. The whole process can be reconstructed logically and in all its detail; every step can be shown and duplicated. This allows for error checking and augmentation if new information becomes available. The appraisal can be seen as a problem-solving technique that can be applied selectively to aspects of a project that are important to that particular project.

Although the materials science appraisal has been applied to recycled construction materials, the appraisal can also be used in road construction and maintenance schemes can involve primary products, non-primary products or a mixture of primary and non-primary products. Hence, it will enable better use of existing materials resource and encourages innovation, i.e. through research and development.

The materials science appraisal can be used to aid engineering decision-making by overcoming issues associated with risks (i.e. using sensitivity analysis) and tracking records of material performance - especially with recycled and secondary materials. The "variability" perception concerning recycled and secondary materials can also be addressed. The appraisal is intended to increase the rational usage of materials (primary and non-primary) in road construction and maintenance. It achieves this in three ways:

1. Providing a paradigm of materials science, which can be used to assess the suitability of materials. The paradigm enables rational thinking under widely varying scenarios relating to road pavements.
2. Increasing confidence in the use of recycled and secondary materials in road construction and maintenance.
3. Describing a number of mitigating generic requirements, which can be employed to enable the use of materials, more especially recycled and secondary materials where the alternative methods indicate that they would not be suitable.

The potential problems regarding the appraisal include the ability to provide repeatability and reproducibility, and subjectivity in generic requirements weighting and product requirement scores. Performance requirement and construction technique are contributing factors to material distress material, but construction technique is not directly catered for within the appraisal. Workmanship can be catered for in the appraisal by altering the values for the generic requirements and/or product score.

Chapter 7 Conclusions and Recommendations

7.1 Introduction

The thesis has reported on the need for a materials science appraisal for recycled materials in roadway applications. The hypothesis of the research was that the proposed materials science appraisal of recycled construction materials for use in roadways is a rational mechanism for supporting engineering decision-making in road construction and maintenance. This hypothesis has been tested throughout the thesis and has resulted in the conclusion that the materials science appraisal is positively a rational mechanism for supporting engineering decision-making in road construction and maintenance.

The research methodology has involved three stages:

1. A literature review on roadway materials, road pavement structure, material properties, technology development, materials testing, materials design, pavement design and modelling.
2. Conceptual development of the materials science appraisal methodology. The development was based on proposing new material-type theories from old theories and three new fundamental material-types have been defined as ceramic-type, metallic-type and polymeric-type (section 4.3) The novel materials science appraisal methodology, which has been developed from the concept, is a systematic process on a macroscopic scale for evaluating the performance of recycled construction materials based on fundamental materials science.
3. Demonstration of how the materials science appraisal can be applied to recycled construction materials and support engineering decision-making.

This research study is based on theory development and testing, which better reflects the practical experience gained. The current theoretical perspective has been established, its application identified, developed and tested to determine its effectiveness. An attempt has been made to increase the knowledge of materials science from a different perspective.

7.2 Materials Science Appraisal and Engineering Decision-making

Chapter 1 introduced contemporary issues in relation to sustainable development and sustainable construction. Linked in to these are that road pavements are expected to perform under increasingly severe conditions and hence materials choice to meet pavement performance requirements has to be wide-ranging an understanding of the underlying theory regarding road materials and their performance is required. There is a need for consistent performance criteria for road pavements to meet customer needs and the variable nature of material source. Hence a rationale for the research in the materials science appraisal of recycled construction materials for roadways.

A review of recycled and secondary materials for use in roadways was presented in Chapter 2, and recommendations were highlighted to encourage the use of recycled construction materials. Proven uses of these materials in roadway applications were presented but the author recognised that applications can be better categorised by material-type and that this form of categorisation can better describe behaviour in an engineering situation.

The broad issues and complexities of road pavement construction and materials, i.e. road pavement structure and materials technology, related to road pavement performance have been addressed in Chapter 3. Chapter 3 focused on the review of roadways in relation to materials, pavement structure, materials testing and design – and critiques the literature for the materials science appraisal. This chapter set a detailed technical background for the thesis. In particular the review highlighted how consistent materials science appraisal can underpin engineering decision-making for roadways and the lack of this consistency.

Chapter 4 described the innovative conceptual development (material-type) of the novel materials science appraisal. The concept defines how materials science can be used to achieve engineering sustainability in road pavement construction and maintenance, while the resulting appraisal is a systematic step-by-step procedure for evaluating the extent of this sustainability. Knowledge of the extent of this sustainability will assist in the engineering decision-making in the use of these materials. The material-type classification can be used to advise on constituents and behavioural properties, and this can be linked to potential road performance using the materials science appraisal. The appraisal allows current, alternative and innovative use of materials technology that will provide best value longer life road constructions. Sensitivity analysis can be incorporated in the procedure, hence engineering decisions can be made and economic and environmental alternative road products can be evaluated.

Chapter 5 demonstrates the application of the novel concept of the materials science appraisal to recycled construction materials and how the materials science appraisal can be applied to the essence of laboratory testing. The results from the materials science appraisal is the calculation of the MS number (red, green or red zone), which, together with sensitivity analysis, gives an informed engineering decision on product choice.

Chapter 6 succinctly integrates the review of information from the literature and describes how the materials science appraisal can be used in a world-wide context and aid engineering decision-making.

7.3 Stakeholders

The materials science appraisal provides a tool that aids engineering decision-making in road construction and maintenance for a variety of stakeholders, i.e. client, consultant, supplier and contractor (section 3.2). Some of these stakeholders may use the materials science appraisal as follows:

- **Regulators, standardisation bodies and specifiers:** national organisations responsible for specifications for highway works and defining methods for testing. They can use the appraisal to evaluate which materials may be used in road construction and the methods for testing.
- **Policy direction groups:** Road Directors and other groups can use the appraisal as a benchmark for encouraging the greater use of recycled construction materials.
- **Highway designers:** These designers can use the materials science appraisal for assurance of properties of road materials.
- **Engineering contractors:** Contractors can use the materials science appraisal to evaluate the potential use of primary and non-primary materials (and their blends) in road construction and maintenance.
- **Scientists and researchers:** The materials science appraisal will be of benefit to scientist and researchers in universities and organisations who

may be carrying out research on related topics, such as roadway materials and construction and engineering decision-making on the use of these materials.

The materials science appraisal can be of benefit to all the above by providing methods for addressing the uncertainties about materials. A system now exists for introducing into designs and any contract the principles of the materials science appraisal that will be of great benefit to industry.

7.4 Recommendations for Future Research

- The concept of a materials-type classification (ceramic-type, metallic-type, polymeric-type, composite-type) requires further investigation. The “products” that can be used in the appraisal are wide and varied in nature and can consider primary, secondary and recycled materials.
- The form of the product could be "pre-formed" (e.g. concrete slabs, metallic forms) or "aggregate" (e.g. road aggregates, PFA, soil). The potential for “recycling by deconstruction” of road components (e.g. concrete slab) and the capability of the appraisal to evaluate product form is an area for future research.
- In-situ and full-scale trials will be required to correlate the laboratory work and to give more credibility to the materials science appraisal.
- The research has investigated the use of recycled materials in road construction. However, the conclusions can be applicable to other construction areas such as earth structures, railway and canal embankments and airport runways and taxiways. Further research will be required in the use of the appraisal in other sectors in the construction.

7.5 Summary

The proposed materials science appraisal has been developed as a rational “think-tank” paradigm-shift for the use of recycled construction materials in roadways. It is considered that the appraisal will support engineering decision in the use of these materials. Encouragement has to be given to “longer-term thinking”. Short-term decisions are often not consistent with the delivery of a viable future in terms of road pavement sustainability. What is required is the development of innovative materials, techniques, and standards, and co-operation between client, research organisations, contractors and manufacturers.

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Appendix A MS Number

The MS number is a function of the weighted scores for each generic requirement of the road product. The weighted score is calculated by multiplying the generic requirement weighting by the square of the road product score (the product score is squared to increase its effect on the sensitivity of the overall performance appraisal). There are three values for the product weighting: 1, 50 and 100; 100 being of more importance and 1 of lower importance. There are four values for the product score: 1, 5, 7 and 10; 10 being the more suitable material-type and 1 being a material of lower suitability. The MS number is calculated using equation A.1.

$$\text{MS Number} = \left(\frac{\text{actual sum of weighted scores}}{\text{ideal sum of weighted scores}}\right) \times 100{,}000 \qquad \text{A.1}$$

The ideal sum of weighted scores is based on product scores for all generic requirements being equal to 10 (10 being the best score for material-type). A factor of 100,000 is applied so that the MS number will be sensitive to changes in generic requirement weighting and product score. The higher the MS number the better the road product. Figure A.1 gives the range of MS numbers – in terms of red, yellow and green zones. Green represents the better road product (MS in the range 70,000 to 100,000); the red the represents the worse road product (MS in the range 1,000 to 30,000) and intermediate between green red and green is yellow (MS in the range 30,000 to 70,000).

The magnitude of the MS number is influenced by the generic requirement weightings of 50 and 100, and whichever product score has at least 10% presence in these weightings. A summary of how the MS number is influenced by the percentage of product scores at weightings of 50 and 100 is shown as Table A.1. The MS number influences have been determined from 1670 possible combinations of generic requirements, summarised in Table A.2 and detailed in Table A.3 to Table A.7.

If all generic requirements have the same product score, irrespective of the weighting, the MS numbers are as follows:

- Product score = 10, MS number = 100000

- Product score = 7, MS number = 49000
- Product score = 5, MS number = 25000
- Product score = 1, MS number = 1000

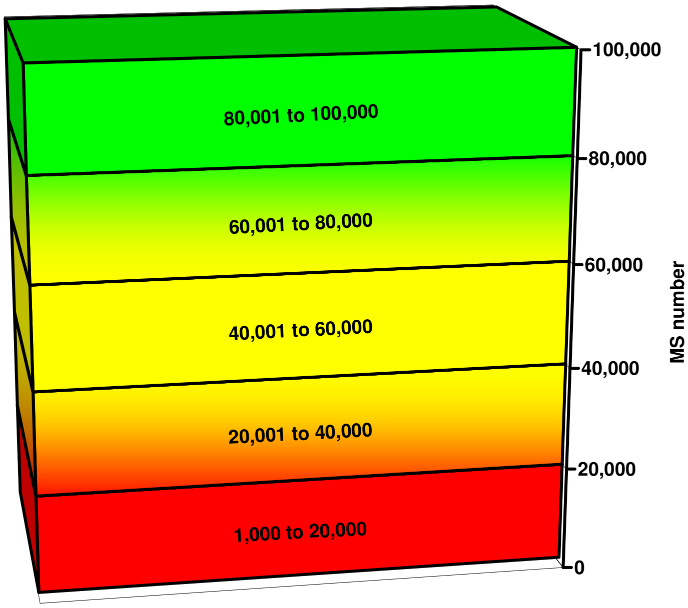
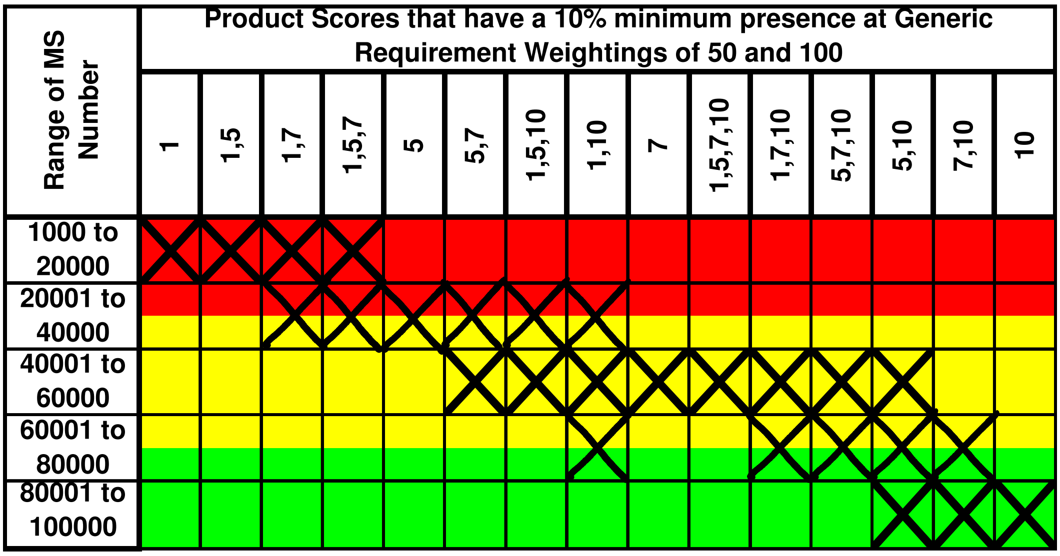


Figure A.1: MS range (red, yellow and green zones)

Table A.1: Probable range of MS number for product score combinations at generic requirement weightings of 50 and 100



X indicates more probable value of MS Number

Table A.2: Number of combinations used to determine MS number

MS number	Number of combinations
1000 to 20000	229
20001 to 40000	513
40001 to 60000	534
60001 to 80000	265
80001 to 100000	129
	Total = 1670

Table A.3: Combinations of generic requirements at MS numbers in the range 1000 to 20000 (details of headings given at end of table)

MS No.	n10010	n10007	n10005	n10001	n05010	n05007	n05005	n05001	n00110	n00107	n00105	n00101	% ps10	% ps7	% ps5	% ps 1
1000				100									0%	0%	0%	100%
1000								100					0%	0%	0%	100%
1000												100	0%	0%	0%	100%
1000				50				50					0%	0%	0%	100%
1000				50								50	0%	0%	0%	100%
1000								50				50	0%	0%	0%	100%
1000				25				25					0%	0%	0%	100%
1000				25								25	0%	0%	0%	100%
1000								25				25	0%	0%	0%	100%
1000				25				25					0%	0%	0%	100%
1000				25								25	0%	0%	0%	100%
1000								25				25	0%	0%	0%	100%
1000				25				25					0%	0%	0%	100%
1000				25								25	0%	0%	0%	100%
1000								25				25	0%	0%	0%	100%
1000				75				75					0%	0%	0%	100%
1000				75								75	0%	0%	0%	100%
1000								75				75	0%	0%	0%	100%
1000				33				33				33	0%	0%	0%	100%
1080				75							25		0%	0%	25%	75%
1158				25				25			25	25	0%	0%	25%	75%
1159								75			25		0%	0%	25%	75%
1159				33				33			33		0%	0%	33%	67%
1159				75						25			0%	25%	0%	75%
1235				33							33	33	0%	0%	33%	67%
1238				50							50		0%	0%	50%	50%
1238				25							25		0%	0%	50%	50%
1238				25							25		0%	0%	50%	50%
1316				25				25		25		25	0%	25%	0%	75%
1318								75		25			0%	25%	0%	75%
1318				33				33		33			0%	33%	0%	67%
1329				75					25				25%	0%	0%	75%
1462								33			33	33	0%	0%	33%	67%
1471								50			50		0%	0%	50%	50%
1471								25			25		0%	0%	50%	50%
1471								25			25		0%	0%	50%	50%
1471				33						33		33	0%	33%	0%	67%
1471				20				20		20	20	20	0%	20%	20%	60%
1474				25				25		25	25		0%	25%	25%	50%
1475				50						50			0%	50%	0%	50%
1475				25						25			0%	50%	0%	50%
1475				25						25			0%	50%	0%	50%
1651				25				25	25			25	25%	0%	0%	75%

Table A.3: Combinations of generic requirements at MS numbers in the range 1000 to 20000 (details of headings given at end of table)

MS No.	n10010	n10007	n10005	n10001	n05010	n05007	n05005	n05001	n00110	n00107	n00105	n00101	% ps10	% ps7	% ps5	% ps 1
1656								75	25				25%	0%	0%	75%
1656				33				33	33				33%	0%	0%	67%
1699				25							75		0%	0%	75%	25%
1699				25						25	25	25	0%	25%	25%	50%
1706				33						33	33		0%	33%	33%	33%
1804				20				20	20		20	20	20%	0%	20%	60%
1809				25				25	25		25		25%	0%	25%	50%
1923								33		33		33	0%	33%	0%	67%
1941								50		50			0%	50%	0%	50%
1941								25		25			0%	50%	0%	50%
1941								25		25			0%	50%	0%	50%
1961				20				20	20	20		20	20%	20%	0%	60%
1967				25				25	25	25			25%	25%	0%	50%
1971				33					33			33	33%	0%	0%	67%
1980				50					50				50%	0%	0%	50%
1980				25					25				50%	0%	0%	50%
1980				25					25				50%	0%	0%	50%
2118				20				20	20	20	20		20%	20%	20%	40%
2154				20						20	60		0%	20%	60%	20%
2194				25					25		25	25	25%	0%	25%	50%
2206				33					33		33		33%	0%	33%	33%
2358								25			75		0%	0%	75%	25%
2358								25		25	25	25	0%	25%	25%	50%
2385								33		33	33		0%	33%	33%	33%
2398				25						75			0%	75%	0%	25%
2427				25					25	25		25	25%	25%	0%	50%
2441				33					33	33			33%	33%	0%	33%
2644				20					20	20	20	20	20%	20%	20%	40%
2660				25					25	25	25		25%	25%	25%	25%
2904								33	33			33	33%	0%	0%	67%
2941								50	50				50%	0%	0%	50%
2941								25	25				50%	0%	0%	50%
2941								25	25				50%	0%	0%	50%
2846				20						80			0%	80%	0%	20%
3257				30					70				70%	0%	0%	30%
3321								25	25		25	25	25%	0%	25%	50%
3365								33	33		33		33%	0%	33%	33%
3717								25		75			0%	75%	0%	25%
3774								25	25	25		25	25%	25%	0%	50%
3827								33	33	33			33%	33%	0%	33%
3883				25					75				75%	0%	0%	25%
4028				10					20	20	15	35	20%	20%	15%	45%
4138				10					20	20	20	30	20%	20%	20%	40%

Table A.3: Combinations of generic requirements at MS numbers in the range 1000 to 20000 (details of headings given at end of table)

MS No.	n10010	n10007	n10005	n10001	n05010	n05007	n05005	n05001	n00110	n00107	n00105	n00101	% ps10	% ps7	% ps5	% ps 1
4167								20	20	20	20	20	20%	20%	20%	40%
4226								25	25	25	25		25%	25%	25%	25%
4429				75			25						0%	0%	25%	75%
5073				10					40		20	30	40%	0%	20%	40%
5111								20	40		20	20	40%	0%	20%	40%
5954				10					40	20	20	10	40%	20%	20%	20%
6000								20	40	20	20		40%	20%	20%	20%
6064				10					40	25	15	10	40%	25%	15%	20%
6111								20	40	25	15		40%	25%	15%	20%
6222								20	40	30	10		40%	30%	10%	20%
6604								25	75				75%	0%	0%	25%
6970				25			25	25				25	0%	0%	25%	75%
7000			25	75									0%	0%	25%	75%
7000							25	75					0%	0%	25%	75%
7000											25	75	0%	0%	25%	75%
7000				33			33	33					0%	0%	33%	67%
7059				20			20	20			20	20	0%	0%	40%	60%
7090				25			25	25			25		0%	0%	50%	50%
7178				20			20	20		20		20	0%	20%	20%	60%
7209				25			25	25		25			0%	25%	25%	50%
7297				20			20	20		20	20		0%	20%	40%	40%
7431				20			20	20	20			20	20%	0%	20%	60%
7463				25			25	25	25				25%	0%	25%	50%
7550				20			20	20	20		20		20%	0%	40%	40%
7668				20			20	20	20	20			20%	20%	20%	40%
7857				75		25							0%	25%	0%	75%
7974				60		20				20			0%	40%	0%	60%
8120				60		20			20				20%	20%	0%	60%
8947				33			33					33	0%	0%	33%	67%
9000				50			50						0%	0%	50%	50%
9000				25			25						0%	0%	50%	50%
9000				25			25						0%	0%	50%	50%
9053				25			25				25	25	0%	0%	50%	50%
9106				33			33				33		0%	0%	67%	33%
9211				25			25			25		25	0%	25%	25%	50%
9265				33			33			33			0%	33%	33%	33%
9314				20			20			20	20	20	0%	20%	40%	40%
9368				25			25			25	25		0%	25%	50%	25%
9546				25			25		25			25	25%	0%	25%	50%
9603				33			33		33				33%	0%	33%	33%
9647				20			20		20		20	20	20%	0%	40%	40%
9704				25			25		25		25		25%	0%	50%	25%
9804				20			20		20	20		20	20%	20%	20%	40%

Table A.3: Combinations of generic requirements at MS numbers in the range 1000 to 20000 (details of headings given at end of table)

MS No.	n10010	n10007	n10005	n10001	n05010	n05007	n05005	n05001	n00110	n00107	n00105	n00101	% ps10	% ps7	% ps5	% ps 1
9862				25			25		25	25			25%	25%	25%	25%
9961				20			20		20	20	20		20%	20%	40%	20%
10039				20			20		20	30	10		20%	30%	30%	20%
10562			25	25				25				25	0%	0%	25%	75%
10600			25					75					0%	0%	25%	75%
10600			33	33				33					0%	0%	33%	67%
10619			20	20				20			20	20	0%	0%	40%	60%
10657			25	25				25			25		0%	0%	50%	50%
10714			20	20				20		20		20	0%	20%	20%	60%
10753			25	25				25		25			0%	25%	25%	50%
10810			20	20				20		20	20		0%	20%	40%	40%
10917			20	20				20	20			20	20%	0%	20%	60%
10950			25	25				20				30	0%	0%	25%	75%
10956			25	25				25	25				25%	0%	25%	50%
11012			20	20				20	20		20		20%	0%	40%	40%
11107			20	20				20	20	20			20%	20%	20%	40%
11914			20					50		30			0%	30%	20%	50%
12026			20					50	10	20			10%	20%	20%	50%
12881							33	33				33	0%	0%	33%	67%
12940			33	33								33	0%	0%	33%	67%
12940				25		25		25				25	0%	25%	0%	75%
12960			20	20			20	20				20	0%	0%	40%	60%
13000			50	50									0%	0%	50%	50%
13000							50	50					0%	0%	50%	50%
13000											50	50	0%	0%	50%	50%
13000			25	25									0%	0%	50%	50%
13000							25	25					0%	0%	50%	50%
13000											25	25	0%	0%	50%	50%
13000			25	25									0%	0%	50%	50%
13000							25	25					0%	0%	50%	50%
13000											25	25	0%	0%	50%	50%
13000		25		75									0%	25%	0%	75%
13000						25		75					0%	25%	0%	75%
13000										25		75	0%	25%	0%	75%
13000				33		33		33					0%	33%	0%	67%
13000			25	25			25	25					0%	0%	50%	50%
13000			25	25							25	25	0%	0%	50%	50%
13000							25	25			25	25	0%	0%	50%	50%
13000				20		20		20			20	20	0%	20%	20%	60%
13040			20	20			20	20			20		0%	0%	60%	40%
13060			33	33							33		0%	0%	67%	33%
13060				25		25		25			25		0%	25%	25%	50%
13119							33	33			33		0%	0%	67%	33%

Table A.3: Combinations of generic requirements at MS numbers in the range 1000 to 20000 (details of headings given at end of table)

MS No.	n10010	n10007	n10005	n10001	n05010	n05007	n05005	n05001	n00110	n00107	n00105	n00101	% ps10	% ps7	% ps5	% ps 1
13119			25	25						25		25	0%	25%	25%	50%
13119				20		20		20		20		20	0%	40%	0%	60%
13120			20	20			20	20		20			0%	20%	40%	40%
13177			20	20						20	20	20	0%	20%	40%	40%
13179			33	33						33			0%	33%	33%	33%
13179				25		25		25		25			0%	50%	0%	50%
13235							25	25		25		25	0%	25%	25%	50%
13238			25	25						25	25		0%	25%	50%	25%
13238				20		20		20		20	20		0%	40%	20%	40%
13289			20	20			20	20	20				20%	0%	40%	40%
13350							20	20		20	20	20	0%	20%	40%	40%
13356							33	33		33			0%	33%	33%	33%
13371			25	25					25			25	25%	0%	25%	50%
13371				20		20		20	20			20	20%	20%	0%	60%
13429			20	20					20		20	20	20%	0%	40%	40%
13433			33	33					33				33%	0%	33%	33%
13433				25		25		25	25				25%	25%	0%	50%
13471							25	25		25	25		0%	25%	50%	25%
13490			25	25					25		25		25%	0%	50%	25%
13490				20		20		20	20		20		20%	20%	20%	40%
13547			20	20					20	20		20	20%	20%	20%	40%
13609			25	25					25	25			25%	25%	25%	25%
13609				20		20		20	20	20			20%	40%	0%	40%
13665			20	20					20	20	20		20%	20%	40%	20%
13735							25	25	25			25	25%	0%	25%	50%
13845							20	20	20		20	20	20%	0%	40%	40%
13861							33	33	33				33%	0%	33%	33%
13971							25	25	25		25		25%	0%	50%	25%
13982				15			35				35	15	0%	0%	70%	30%
14014				10			20		20	20		30	20%	20%	20%	40%
14078							20	20	20	20		20	20%	20%	20%	40%
14206							25	25	25	25			25%	25%	25%	25%
14311							20	20	20	20	20		20%	20%	40%	20%
15143				75	25								25%	0%	0%	75%
15343			25	25			25					25	0%	0%	50%	50%
15343				20		20	20	20				20	0%	20%	20%	60%
15381			20	20			20				20	20	0%	0%	60%	40%
15400				25			75						0%	0%	75%	25%
15400			33	33			33						0%	0%	67%	33%
15400				25		25	25	25					0%	25%	25%	50%
15438			25	25			25				25		0%	0%	75%	25%
15438				20		20	20	20			20		0%	20%	40%	40%
15476			20	20			20			20		20	0%	20%	40%	40%

Table A.3: Combinations of generic requirements at MS numbers in the range 1000 to 20000 (details of headings given at end of table)

MS No.	n10010	n10007	n10005	n10001	n05010	n05007	n05005	n05001	n00110	n00107	n00105	n00101	% ps10	% ps7	% ps5	% ps 1
15534			25	25			25			25			0%	25%	50%	25%
15534				20		20	20	20		20			0%	40%	20%	40%
15571			20	20			20			20	20		0%	20%	60%	20%
15679			20	20			20		20			20	20%	0%	40%	40%
15737			25	25			25		25				25%	0%	50%	25%
15737				20		20	20	20	20				20%	20%	20%	40%
15774			20	20			20		20		20		20%	0%	60%	20%
15869			20	20			20		20	20			20%	20%	40%	20%
15970			20	20			20		30	10			30%	10%	40%	20%
16071			20	20			20		40				40%	0%	40%	20%
16894			33					33				33	0%	0%	33%	67%
16894				33		33						33	0%	33%	0%	67%
16947			20	20		20		20				20	0%	20%	20%	60%
16947			25					25			25	25	0%	0%	50%	50%
16947				25		25					25	25	0%	25%	25%	50%
17000			50					50					0%	0%	50%	50%
17000				50		50							0%	50%	0%	50%
17000			25					25					0%	0%	50%	50%
17000				25		25							0%	50%	0%	50%
17000			25					25					0%	0%	50%	50%
17000				25		25							0%	50%	0%	50%
17000			25	25		25		25					0%	25%	25%	50%
17027			20	20		20		20			20		0%	20%	40%	40%
17053			33					33			33		0%	0%	67%	33%
17053				33		33					33		0%	33%	33%	33%
17105			25					25		25		25	0%	25%	25%	50%
17105				25		25				25		25	0%	50%	0%	50%
17106			20	20		20		20		20			0%	40%	20%	40%
17157			20					20		20	20	20	0%	20%	40%	40%
17157				20		20				20	20	20	0%	40%	20%	40%
17212			33					33		33			0%	33%	33%	33%
17212				33		33				33			0%	67%	0%	33%
17263			25					25		25	25		0%	25%	50%	25%
17263				25		25				25	25		0%	50%	25%	25%
17276			20	20		20		20	20				20%	20%	20%	40%
17441			25					25	25			25	25%	0%	25%	50%
17441				25		25			25			25	25%	25%	0%	50%
17490			20					20	20		20	20	20%	0%	40%	40%
17490				20		20			20		20	20	20%	20%	20%	40%
17550			33					33	33				33%	0%	33%	33%
17550				33		33			33				33%	33%	0%	33%
17599			25					25	25		25		25%	0%	50%	25%
17599				25		25			25		25		25%	25%	25%	25%

Table A.3: Combinations of generic requirements at MS numbers in the range 1000 to 20000 (details of headings given at end of table)

MS No.	n10010	n10007	n10005	n10001	n05010	n05007	n05005	n05001	n00110	n00107	n00105	n00101	% ps10	% ps7	% ps5	% ps 1
17647			20					20	20	20		20	20%	20%	20%	40%
17647				20		20			20	20		20	20%	40%	0%	40%
17757			25					25	25	25			25%	25%	25%	25%
17757				25		25			25	25			25%	50%	0%	25%
17804			20					20	20	20	20		20%	20%	40%	20%
17804				20		20			20	20	20		20%	40%	20%	20%
17971			20					20	30	10	20		30%	10%	40%	20%
18143			20	20		20	20	20					0%	20%	40%	40%
18910			25				25	25				25	0%	0%	50%	50%
18910				25		25	25					25	0%	25%	25%	50%
18941			20				20	20			20	20	0%	0%	60%	40%
18941				20		20	20				20	20	0%	20%	40%	40%
19000			75	25									0%	0%	75%	25%
19000							75	25					0%	0%	75%	25%
19000											75	25	0%	0%	75%	25%
19000			33				33	33					0%	0%	67%	33%
19000				33		33	33						0%	33%	33%	33%
19030			25				25	25			25		0%	0%	75%	25%
19030				25		25	25				25		0%	25%	50%	25%
19059			20				20	20		20		20	0%	20%	40%	40%
19059				20		20	20			20		20	0%	40%	20%	40%
19149			25				25	25		25			0%	25%	50%	25%
19149				25		25	25			25			0%	50%	25%	25%
19178			20				20	20		20	20		0%	20%	60%	20%
19178				20		20	20			20	20		0%	40%	40%	20%
19312			20				20	20	20			20	20%	0%	40%	40%
19312				20		20	20		20			20	20%	20%	20%	40%
19403			25				25	25	25				25%	0%	50%	25%
19403				25		25	25		25				25%	25%	25%	25%
19431			20				20	20	20		20		20%	0%	60%	20%
19431				20		20	20		20		20		20%	20%	40%	20%
19550			20				20	20	20	20			20%	20%	40%	20%
19550				20		20	20		20	20			20%	40%	20%	20%

Table A.3: Combinations of generic requirements at MS numbers in the range 1000 to 20000 (details of headings given at end of table)

MS No.	n10010	n10007	n10005	n10001	n05010	n05007	n05005	n05001	n00110	n00107	n00105	n00101	% ps10	% ps7	% ps5	% ps 1
19802			20				20	20	40				40%	0%	40%	20%

Notes:

MS No.	MS number
n10010	Number of generic requirements with a weighting of 100 and product score of 10
n10007	Number of generic requirements with a weighting of 100 and product score of 7
n10005	Number of generic requirements with a weighting of 100 and product score of 5
n10001	number of generic requirements with a weighting of 100 and product score of 1
n05010	number of generic requirements with a weighting of 50 and product score of 10
n05007	number of generic requirements with a weighting of 50 and product score of 7
n05005	number of generic requirements with a weighting of 50 and product score of 5
n05001	number of generic requirements with a weighting of 50 and product score of 1
n00110	number of generic requirements with a weighting of 1 and product score of 10
n00107	number of generic requirements with a weighting of 1 and product score of 7
n00105	number of generic requirements with a weighting of 1 and product score of 5
n00101	number of generic requirements with a weighting of 1 and product score of 1
%ps10	percentage of generic requirements with a product score of 10
%ps7	percentage of generic requirements with a product score of 7
%ps5	percentage of generic requirements with a product score of 5
%ps1	percentage of generic requirements with a product score of 1

Table A.4: Combinations of generic requirements at MS numbers in the range 20001 to 40000 (details of headings given at end of table)

MS No.	n10010	n10007	n10005	n10001	n05010	n05007	n05005	n05001	n00110	n00107	n00105	n00101	% ps10	% ps7	% ps5	% ps 1
20124		25		25				25				25	0%	25%	0%	75%
20124			25	25		25						25	0%	25%	25%	50%
20143		20		20				20			20	20	0%	20%	20%	60%
20143			20	20		20					20	20	0%	20%	40%	40%
20200		25						75					0%	25%	0%	75%
20200		33		33				33					0%	33%	0%	67%
20200			33	33		33							0%	33%	33%	33%
20219		25		25				25			25		0%	25%	25%	50%
20219			25	25		25					25		0%	25%	50%	25%
20238		20		20				20		20		20	0%	40%	0%	60%
20238			20	20		20				20		20	0%	40%	20%	40%
20315		25		25				25		25			0%	50%	0%	50%
20315			25	25		25				25			0%	50%	25%	25%
20333		20		20				20		20	20		0%	40%	20%	40%
20333			20	20		20				20	20		0%	40%	40%	20%
20440		20		20				20	20			20	20%	20%	0%	60%

Table A.4: Combinations of generic requirements at MS numbers in the range 20001 to 40000 (details of headings given at end of table)

MS No.	n10010	n10007	n10005	n10001	n05010	n05007	n05005	n05001	n00110	n00107	n00105	n00101	% ps10	% ps7	% ps5	% ps 1
20440			20	20		20			20			20	20%	20%	20%	40%
20518		25		25				25	25				25%	25%	0%	50%
20518			25	25		25			25				25%	25%	25%	25%
20536		20		20				20	20		20		20%	20%	20%	40%
20536			20	20		20			20		20		20%	20%	40%	20%
20631		20		20				20	20	20			20%	40%	0%	40%
20631			20	20		20			20	20			20%	40%	20%	20%
20934		20		20			20	20				20	0%	20%	20%	60%
20934			20	20		20	20					20	0%	20%	40%	40%
21000		25		25			25	25					0%	25%	25%	50%
21000			25	25		25	25						0%	25%	50%	25%
21013		20		20			20	20			20		0%	20%	40%	40%
21013			20	20		20	20				20		0%	20%	60%	20%
21093		20		20			20	20		20			0%	40%	20%	40%
21093			20	20		20	20			20			0%	40%	40%	20%
21262		20		20			20	20	20				20%	20%	20%	40%
21262			20	20		20	20		20				20%	20%	40%	20%
21513		20	20	20				20				20	0%	20%	20%	60%
21571			75					25					0%	0%	75%	25%
21571		25	25	25				25					0%	25%	25%	50%
21581		20	20	20				20			20		0%	20%	40%	40%
21650		20	20	20				20		20			0%	40%	20%	40%
21795		20	20	20				20	20				20%	20%	20%	40%
22000		20	20	20			20	20					0%	20%	40%	40%
22091		20	25	20			15	20					0%	20%	40%	40%
22882		20	30	20			15	15					0%	20%	45%	35%
23239			10								10	80	0%	0%	20%	80%
23940			15								15	70	0%	0%	30%	70%
24016			15								20	65	0%	0%	35%	65%
24301			25									75	0%	0%	25%	75%
24762			50									50	0%	0%	50%	50%
24762			25									25	0%	0%	50%	50%
24762			25									25	0%	0%	50%	50%
24765			33								33	33	0%	0%	67%	33%
24841			33				33					33	0%	0%	67%	33%
24842			25				25				25	25	0%	0%	75%	25%
24881		33		33								33	0%	33%	0%	67%
24881			25			25		25				25	0%	25%	25%	50%
24881		25		25							25	25	0%	25%	25%	50%
24881			20			20		20			20	20	0%	20%	40%	40%
24904		25		25			25					25	0%	25%	25%	50%
24904			20			20	20	20				20	0%	20%	40%	40%
24905		20		20			20				20	20	0%	20%	40%	40%

Table A.4: Combinations of generic requirements at MS numbers in the range 20001 to 40000 (details of headings given at end of table)

MS No.	n10010	n10007	n10005	n10001	n05010	n05007	n05005	n05001	n00110	n00107	n00105	n00101	% ps10	% ps7	% ps5	% ps 1
24920			75									25	0%	0%	75%	25%
24920		25	25	25								25	0%	25%	25%	50%
24920		20		20		20		20				20	0%	40%	0%	60%
24921		20	20	20							20	20	0%	20%	40%	40%
24932		20	20	20			20					20	0%	20%	40%	40%
25000			100										0%	0%	100%	0%
25000		50		50									0%	50%	0%	50%
25000			50				50						0%	0%	100%	0%
25000			50								50		0%	0%	100%	0%
25000		25		25									0%	50%	0%	50%
25000			25				25						0%	0%	100%	0%
25000			25								25		0%	0%	100%	0%
25000			25				25						0%	0%	100%	0%
25000			25								25		0%	0%	100%	0%
25000		25		25									0%	50%	0%	50%
25000			75				75						0%	0%	100%	0%
25000			75								75		0%	0%	100%	0%
25000			25				25						0%	0%	100%	0%
25000			25								25		0%	0%	100%	0%
25000		33	33	33									0%	33%	33%	33%
25000		33		33			33						0%	33%	33%	33%
25000		33		33							33		0%	33%	33%	33%
25000			33			33		33					0%	33%	33%	33%
25000			33				33				33		0%	0%	100%	0%
25000			33							33		33	0%	33%	33%	33%
25000		25	25	25			25						0%	25%	50%	25%
25000		25	25	25							25		0%	25%	50%	25%
25000		25		25		25		25					0%	50%	0%	50%
25000		25		25			25				25		0%	25%	50%	25%
25000		25		25						25		25	0%	50%	0%	50%
25000			25			25	25	25					0%	25%	50%	25%
25000			25			25		25			25		0%	25%	50%	25%
25000			25				25			25		25	0%	25%	50%	25%
25000			25							25	25	25	0%	25%	50%	25%
25000		20	20	20		20		20					0%	40%	20%	40%
25000		20	20	20			20				20		0%	20%	60%	20%
25000		20	20	20						20		20	0%	40%	20%	40%
25000		20		20		20	20	20					0%	40%	20%	40%
25000		20		20		20		20			20		0%	40%	20%	40%
25000		20		20			20			20		20	0%	40%	20%	40%
25000		20		20						20	20	20	0%	40%	20%	40%
25000			20			20	20	20			20		0%	20%	60%	20%
25000			20			20		20		20		20	0%	40%	20%	40%

Table A.4: Combinations of generic requirements at MS numbers in the range 20001 to 40000 (details of headings given at end of table)

MS No.	n10010	n10007	n10005	n10001	n05010	n05007	n05005	n05001	n00110	n00107	n00105	n00101	% ps10	% ps7	% ps5	% ps 1
25000			20				20			20	20	20	0%	20%	60%	20%
25068		20	20	20			20			20			0%	40%	40%	20%
25079		20	20	20						20	20		0%	40%	40%	20%
25080			75							25			0%	25%	75%	0%
25080		25	25	25						25			0%	50%	25%	25%
25080		20		20		20		20		20			0%	60%	0%	40%
25095		20		20			20			20	20		0%	40%	40%	20%
25096		25		25			25			25			0%	50%	25%	25%
25096			20			20	20	20		20			0%	40%	40%	20%
25119		25		25						25	25		0%	50%	25%	25%
25119			20			20		20		20	20		0%	40%	40%	20%
25119		33		33						33			0%	67%	0%	33%
25119			25			25		25		25			0%	50%	25%	25%
25158			25				25			25	25		0%	25%	75%	0%
25159			33				33			33			0%	33%	67%	0%
25165		10	10	10		10	10	10	10	10	10	10	10%	30%	30%	30%
25169		20	20	20					20			20	20%	20%	20%	40%
25202		20		20			20		20			20	20%	20%	20%	40%
25214		20	20	20			20		20				20%	20%	40%	20%
25235			33							33	33		0%	33%	67%	0%
25238			50							50			0%	50%	50%	0%
25238			25							25			0%	50%	50%	0%
25238			25							25			0%	50%	50%	0%
25248		20	20	20					20		20		20%	20%	40%	20%
25249			75						25				25%	0%	75%	0%
25249		25	25	25					25				25%	25%	25%	25%
25249		20		20		20		20	20				20%	40%	0%	40%
25251		20		20					20		20	20	20%	20%	20%	40%
25252		25		25					25			25	25%	25%	0%	50%
25252			20			20		20	20			20	20%	20%	20%	40%
25298		20		20			20		20		20		20%	20%	40%	20%
25299		25		25			25		25				25%	25%	25%	25%
25299			20			20	20	20	20				20%	20%	40%	20%
25328		20	20	20					20	20			20%	40%	20%	20%
25333			20				20		20		20	20	20%	0%	60%	20%
25336			25				25		25			25	25%	0%	50%	25%
25369		20		20					20	20		20	20%	40%	0%	40%
25371		25		25					25		25		25%	25%	25%	25%
25371			20			20		20	20		20		20%	20%	40%	20%
25373		33		33					33				33%	33%	0%	33%
25373			25			25		25	25				25%	25%	25%	25%
25393		20		20			20		20	20			20%	40%	20%	20%
25419			20	20	20			20				20	20%	0%	20%	60%

Table A.4: Combinations of generic requirements at MS numbers in the range 20001 to 40000 (details of headings given at end of table)

MS No.	n10010	n10007	n10005	n10001	n05010	n05007	n05005	n05001	n00110	n00107	n00105	n00101	% ps10	% ps7	% ps5	% ps 1
25429			20	20	20		20	20					20%	0%	40%	40%
25488		20		20					20	20	20		20%	40%	20%	20%
25490		25		25					25	25			25%	50%	0%	25%
25490			20			20		20	20	20			20%	40%	20%	20%
25490			20				20		20	20		20	20%	20%	40%	20%
25493			25				25		25		25		25%	0%	75%	0%
25495			25						25		25	25	25%	0%	50%	25%
25497			33				33		33				33%	0%	67%	0%
25498			20	20	20			20			20		20%	0%	40%	40%
25500			33						33			33	33%	0%	33%	33%
25500			25	25	25			25					25%	0%	25%	50%
25502				20	20		20	20				20	20%	0%	20%	60%
25578			20	20	20			20		20			20%	20%	20%	40%
25598				20	20		20	20			20		20%	0%	40%	40%
25600				25	25		25	25					25%	0%	25%	50%
25624				20	20			20			20	20	20%	0%	20%	60%
25627				25	25			25				25	25%	0%	0%	75%
25647			20				20		20	20	20		20%	20%	60%	0%
25651			25				25		25	25			25%	25%	50%	0%
25693				20	20		20	20		20			20%	20%	20%	40%
25699			25							75			0%	75%	25%	0%
25721			20						20	20	20	20	20%	20%	40%	20%
25728			25						25	25		25	25%	25%	25%	25%
25735			33						33		33		33%	0%	67%	0%
25743			50						50				50%	0%	50%	0%
25743			25						25				50%	0%	50%	0%
25743			25						25				50%	0%	50%	0%
25743				20	20			20		20		20	20%	20%	0%	60%
25746				25	25			25			25		25%	0%	25%	50%
25748			20	20	20			20	20				40%	0%	20%	40%
25750	25			75									25%	0%	0%	75%
25750				33	33			33					33%	0%	0%	67%
25861				20	20			20		20	20		20%	20%	20%	40%
25866				25	25			25		25			25%	25%	0%	50%
25896				20	20		20	20	20				40%	0%	20%	40%
25961			25						25	25	25		25%	25%	50%	0%
25971			33						33	33			33%	33%	33%	0%
25995				20	20			20	20			20	40%	0%	0%	60%
26114				20	20			20	20		20		40%	0%	20%	40%
26119				25	25			25	25				50%	0%	0%	50%
26233				20	20			20	20	20			40%	20%	0%	40%
26480				20	15		5	5	40			15	55%	0%	5%	40%
26516				20	15		5	5	40		5	10	55%	0%	10%	35%

Table A.4: Combinations of generic requirements at MS numbers in the range 20001 to 40000 (details of headings given at end of table)

MS No.	n10010	n10007	n10005	n10001	n05010	n05007	n05005	n05001	n00110	n00107	n00105	n00101	% ps10	% ps7	% ps5	% ps 1
26589				20	15		5	5	40		15		55%	0%	20%	25%
27184			25						75				75%	0%	25%	0%
28000		20	20	20		20	20						0%	40%	40%	20%
28164		20	20	20		20	10					10	0%	40%	30%	30%
28350		20	20	20		20						20	0%	40%	20%	40%
28419		20	20	20		20					20		0%	40%	40%	20%
28429			75			25							0%	25%	75%	0%
28429		25	25	25		25							0%	50%	25%	25%
28487		20	20	20		20				20			0%	60%	20%	20%
28527			10	10	10	10	10	10	10	10	10	10	20%	20%	30%	30%
28632		20	20	20		20			20				20%	40%	20%	20%
28857			20	20	20	20		20					20%	20%	20%	40%
28907		20	20				20	20				20	0%	20%	40%	40%
28907		20		20		20	20					20	0%	40%	20%	40%
28987		20	20				20	20			20		0%	20%	60%	20%
28987		20		20		20	20				20		0%	40%	40%	20%
29000		25	25				25	25					0%	25%	50%	25%
29000		25		25		25	25						0%	50%	25%	25%
29066		20	20				20	20		20			0%	40%	40%	20%
29066		20		20		20	20			20			0%	60%	20%	20%
29236		20	20				20	20	20				20%	20%	40%	20%
29236		20		20		20	20		20				20%	40%	20%	20%
29405			20	20	20		20					20	20%	0%	40%	40%
29485			20	20	20		20				20		20%	0%	60%	20%
29500			25	25	25		25						25%	0%	50%	25%
29500				20	20	20	20	20					20%	20%	20%	40%
29565			20	20	20		20			20			20%	20%	40%	20%
29667		20	20					20			20	20	0%	20%	40%	40%
29667		20		20		20					20	20	0%	40%	20%	40%
29685		25	25					25				25	0%	25%	25%	50%
29685		25		25		25						25	0%	50%	0%	50%
29734			20	20	20		20		20				40%	0%	40%	20%
29762		20	20					20		20		20	0%	40%	20%	40%
29762		20		20		20				20		20	0%	60%	0%	40%
29781		25	25					25			25		0%	25%	50%	25%
29781		25		25		25					25		0%	50%	25%	25%
29800				25		75							0%	75%	0%	25%
29800		33	33					33					0%	33%	33%	33%
29800		33		33		33							0%	67%	0%	33%
29857		20	20					20		20	20		0%	40%	40%	20%
29857		20		20		20				20	20		0%	60%	20%	20%
29876		25	25					25		25			0%	50%	25%	25%
29876		25		25		25				25			0%	75%	0%	25%

Table A.4: Combinations of generic requirements at MS numbers in the range 20001 to 40000 (details of headings given at end of table)

MS No.	n10010	n10007	n10005	n10001	n05010	n05007	n05005	n05001	n00110	n00107	n00105	n00101	% ps10	% ps7	% ps5	% ps 1
29964		20	20					20	20			20	20%	20%	20%	40%
29964		20		20		20			20			20	20%	40%	0%	40%
30060		20	20					20	20		20		20%	20%	40%	20%
30060		20		20		20			20		20		20%	40%	20%	20%
30080		25	25					25	25				25%	25%	25%	25%
30080		25		25		25			25				25%	50%	0%	25%
30155		20	20					20	20	20			20%	40%	20%	20%
30155		20		20		20			20	20			20%	60%	0%	20%
30262			20	20	20						20	20	20%	0%	40%	40%
30283			25	25	25							25	25%	0%	25%	50%
30283				20	20	20		20				20	20%	20%	0%	60%
30357			20	20	20					20		20	20%	20%	20%	40%
30378			25	25	25						25		25%	0%	50%	25%
30378				20	20	20		20			20		20%	20%	20%	40%
30400			33	33	33								33%	0%	33%	33%
30400				25	25	25		25					25%	25%	0%	50%
30452			20	20	20					20	20		20%	20%	40%	20%
30474			25	25	25					25			25%	25%	25%	25%
30474				20	20	20		20		20			20%	40%	0%	40%
30560			20	20	20				20			20	40%	0%	20%	40%
30655			20	20	20				20		20		40%	0%	40%	20%
30677			25	25	25				25				50%	0%	25%	25%
30677				20	20	20		20	20				40%	20%	0%	40%
30750			20	20	20				20	20			40%	20%	20%	20%
30782		10	10	10	10		10	10	10	10	10	10	20%	20%	30%	30%
30822		20					20	20			20	20	0%	20%	40%	40%
30822			20			20	20				20	20	0%	20%	60%	20%
30851		25					25	25				25	0%	25%	25%	50%
30851			25			25	25					25	0%	25%	50%	25%
30941		20					20	20		20		20	0%	40%	20%	40%
30941			20			20	20			20		20	0%	40%	40%	20%
30970		25					25	25			25		0%	25%	50%	25%
30970			25			25	25				25		0%	25%	75%	0%
31000		25	75										0%	25%	75%	0%
31000		33					33	33					0%	33%	33%	33%
31000			33			33	33						0%	33%	67%	0%
31059		20					20	20		20	20		0%	40%	40%	20%
31059			20			20	20			20	20		0%	40%	60%	0%
31090		25					25	25		25			0%	50%	25%	25%
31090			25			25	25			25			0%	50%	50%	0%
31193		20					20	20	20			20	20%	20%	20%	40%
31193			20			20	20		20			20	20%	20%	40%	20%
31312		20					20	20	20		20		20%	20%	40%	20%

Table A.4: Combinations of generic requirements at MS numbers in the range 20001 to 40000 (details of headings given at end of table)

MS No.	n10010	n10007	n10005	n10001	n05010	n05007	n05005	n05001	n00110	n00107	n00105	n00101	% ps10	% ps7	% ps5	% ps 1
31312			20			20	20		20		20		20%	20%	60%	0%
31343		25					25	25	25				25%	25%	25%	25%
31343			25			25	25		25				25%	25%	50%	0%
31375		20	20	20	20			20					20%	20%	20%	40%
31431		20					20	20	20	20			20%	40%	20%	20%
31431			20			20	20		20	20			20%	40%	40%	0%
31564				20	20		20				20	20	20%	0%	40%	40%
31597				25	25		25					25	25%	0%	25%	50%
31683				20	20		20			20		20	20%	20%	20%	40%
31716				25	25		25				25		25%	0%	50%	25%
31750				33	33		33						33%	0%	33%	33%
31802				20	20		20			20	20		20%	20%	40%	20%
31836				25	25		25			25			25%	25%	25%	25%
31857		20	20			20	20	20					0%	40%	40%	20%
31936				20	20		20		20			20	40%	0%	20%	40%
32054				20	20		20		20		20		40%	0%	40%	20%
32090				25	25		25		25				50%	0%	25%	25%
32173				20	20		20		20	20			40%	20%	20%	20%
32286		20		20	20		20	20					20%	20%	20%	40%
32286			20	20	20	20	20						20%	20%	40%	20%
32455		10	10	10	10	10	10	10		10	10	10	10%	30%	30%	30%
32557		10	10	10	10	10	10	10	10		10	10	20%	20%	30%	30%
32604		10	10	10	10	10	10	10	10	10		10	20%	30%	20%	30%
32652		10	10	10	10	10	10	10	10	10	10		20%	30%	30%	20%
32737		25						25			25	25	0%	25%	25%	50%
32737			25			25					25	25	0%	25%	50%	25%
32788		33						33				33	0%	33%	0%	67%
32788			33			33						33	0%	33%	33%	33%
32843		20						20		20	20	20	0%	40%	20%	40%
32843			20			20				20	20	20	0%	40%	40%	20%
32894		20	20			20		20				20	0%	40%	20%	40%
32895		25						25		25		25	0%	50%	0%	50%
32895			25			25				25		25	0%	50%	25%	25%
32947		33						33			33		0%	33%	33%	33%
32947			33			33					33		0%	33%	67%	0%
32973		20	20			20		20			20		0%	40%	40%	20%
33000		50						50					0%	50%	0%	50%
33000			50			50							0%	50%	50%	0%
33000		25						25					0%	50%	0%	50%
33000			25			25							0%	50%	50%	0%
33000		25						25					0%	50%	0%	50%
33000			25			25							0%	50%	50%	0%
33000		25	25			25		25					0%	50%	25%	25%

Table A.4: Combinations of generic requirements at MS numbers in the range 20001 to 40000 (details of headings given at end of table)

MS No.	n10010	n10007	n10005	n10001	n05010	n05007	n05005	n05001	n00110	n00107	n00105	n00101	% ps10	% ps7	% ps5	% ps 1
33053		25						25		25	25		0%	50%	25%	25%
33053			25			25				25	25		0%	50%	50%	0%
33053		20	20			20		20		20			0%	60%	20%	20%
33106		33						33		33			0%	67%	0%	33%
33106			33			33				33			0%	67%	33%	0%
33176		20						20	20		20	20	20%	20%	20%	40%
33176			20			20			20		20	20	20%	20%	40%	20%
33223		20	20			20		20	20				20%	40%	20%	20%
33230		25						25	25			25	25%	25%	0%	50%
33230			25			25			25			25	25%	25%	25%	25%
33333		20						20	20	20		20	20%	40%	0%	40%
33333			20			20			20	20		20	20%	40%	20%	20%
33388		25						25	25		25		25%	25%	25%	25%
33388			25			25			25		25		25%	25%	50%	0%
33392		20		20	20			20				20	20%	20%	0%	60%
33392			20	20	20	20						20	20%	20%	20%	40%
33425		10	10	10	10	10		10	10	10	10	10	20%	30%	20%	30%
33444		33						33	33				33%	33%	0%	33%
33444			33			33			33				33%	33%	33%	0%
33472		20		20	20			20			20		20%	20%	20%	40%
33472			20	20	20	20					20		20%	20%	40%	20%
33490		20						20	20	20	20		20%	40%	20%	20%
33490			20			20			20	20	20		20%	40%	40%	0%
33500		25		25	25			25					25%	25%	0%	50%
33500			25	25	25	25							25%	25%	25%	25%
33546		25						25	25	25			25%	50%	0%	25%
33546			25			25			25	25			25%	50%	25%	0%
33551		20		20	20			20		20			20%	40%	0%	40%
33551			20	20	20	20				20			20%	40%	20%	20%
33721		20		20	20			20	20				40%	20%	0%	40%
33721			20	20	20	20			20				40%	20%	20%	20%
33724				25	25						25	25	25%	0%	25%	50%
33781				33	33							33	33%	0%	0%	67%
33824				20	20					20	20	20	20%	20%	20%	40%
33882				25	25					25		25	25%	25%	0%	50%
33940				33	33						33		33%	0%	33%	33%
34000				50	50								50%	0%	0%	50%
34000				25	25								50%	0%	0%	50%
34000				25	25								50%	0%	0%	50%
34039				25	25					25	25		25%	25%	25%	25%
34099				33	33					33			33%	33%	0%	33%
34157				20	20				20		20	20	40%	0%	20%	40%
34217				25	25				25			25	50%	0%	0%	50%

Table A.4: Combinations of generic requirements at MS numbers in the range 20001 to 40000 (details of headings given at end of table)

MS No.	n10010	n10007	n10005	n10001	n05010	n05007	n05005	n05001	n00110	n00107	n00105	n00101	% ps10	% ps7	% ps5	% ps 1
34314				20	20				20	20		20	40%	20%	0%	40%
34375				25	25				25		25		50%	0%	25%	25%
34375		20	20	20	20		20						20%	20%	40%	20%
34429		20	20				20				20	20	0%	20%	60%	20%
34437				33	33				33				67%	0%	0%	33%
34466		25	25				25					25	0%	25%	50%	25%
34466		20				20	20	20				20	0%	40%	20%	40%
34468		10		10	10	10	10	10	10	10	10	10	20%	30%	20%	30%
34471				20	20				20	20	20		40%	20%	20%	20%
34524		20	20				20			20		20	0%	40%	40%	20%
34533				25	25				25	25			50%	25%	0%	25%
34562		25	25				25				25		0%	25%	75%	0%
34562		20				20	20	20			20		0%	40%	40%	20%
34600		25					75						0%	25%	75%	0%
34600		33	33				33						0%	33%	67%	0%
34600		25				25	25	25					0%	50%	25%	25%
34619		20	20				20			20	20		0%	40%	60%	0%
34657		25	25				25			25			0%	50%	50%	0%
34657		20				20	20	20		20			0%	60%	20%	20%
34726		20	20				20		20			20	20%	20%	40%	20%
34750	20		20	20			20	20					20%	0%	40%	40%
34821		20	20				20		20		20		20%	20%	60%	0%
34861		25	25				25		25				25%	25%	50%	0%
34861		20				20	20	20	20				20%	40%	20%	20%
34917		20	20				20		20	20			20%	40%	40%	0%
35064			20		20		20	20				20	20%	0%	40%	40%
35064				20	20	20	20					20	20%	20%	20%	40%
35159			20		20		20	20			20		20%	0%	60%	20%
35159				20	20	20	20				20		20%	20%	40%	20%
35200			25		25		25	25					25%	0%	50%	25%
35200				25	25	25	25						25%	25%	25%	25%
35255			20		20		20	20		20			20%	20%	40%	20%
35255				20	20	20	20			20			20%	40%	20%	20%
35458			20		20		20	20	20				40%	0%	40%	20%
35458				20	20	20	20		20				40%	20%	20%	20%
35615		20	20	20	20							20	20%	20%	20%	40%
35684		20	20	20	20						20		20%	20%	40%	20%
35714			75		25								25%	0%	75%	0%
35714		25	25	25	25								25%	25%	25%	25%
35714		20		20	20	20		20					20%	40%	0%	40%
35752		20	20	20	20					20			20%	40%	20%	20%
35897		20	20	20	20				20				40%	20%	20%	20%
36043	20		20	20				20				20	20%	0%	20%	60%

Table A.4: Combinations of generic requirements at MS numbers in the range 20001 to 40000 (details of headings given at end of table)

MS No.	n10010	n10007	n10005	n10001	n05010	n05007	n05005	n05001	n00110	n00107	n00105	n00101	% ps10	% ps7	% ps5	% ps 1
36068		10	10	10	10	10	10		10	10	10	10	20%	30%	30%	20%
36111	20		20	20				20			20		20%	0%	40%	40%
36143	25		25	25				25					25%	0%	25%	50%
36179	20		20	20				20		20			20%	20%	20%	40%
36325	20		20	20				20	20				40%	0%	20%	40%
36399	10		10	10		10	10	10	10	10	10	10	20%	20%	30%	30%
36762		25	25								25	25	0%	25%	50%	25%
36762		20				20		20			20	20	0%	40%	20%	40%
36821		33	33									33	0%	33%	33%	33%
36821		25				25		25				25	0%	50%	0%	50%
36823		20	20							20	20	20	0%	40%	40%	20%
36880		20	20			20	20					20	0%	40%	40%	20%
36881		25	25							25		25	0%	50%	25%	25%
36881		20				20		20		20		20	0%	60%	0%	40%
36940		33	33								33		0%	33%	67%	0%
36940		25				25		25			25		0%	50%	25%	25%
36960		20	20			20	20				20		0%	40%	60%	0%
37000		50	50										0%	50%	50%	0%
37000		25	25										0%	50%	50%	0%
37000		75		25									0%	75%	0%	25%
37000		25	25										0%	50%	50%	0%
37000		33				33		33					0%	67%	0%	33%
37000		25	25			25	25						0%	50%	50%	0%
37000		25	25							25	25		0%	50%	50%	0%
37000		20				20		20		20	20		0%	60%	20%	20%
37040		20	20			20	20			20			0%	60%	40%	0%
37060		33	33							33			0%	67%	33%	0%
37060		25				25		25		25			0%	75%	0%	25%
37074		20	20						20		20	20	20%	20%	40%	20%
37134		25	25						25			25	25%	25%	25%	25%
37134		20				20		20	20			20	20%	40%	0%	40%
37192		20	20						20	20		20	20%	40%	20%	20%
37209		20	20			20	20		20				20%	40%	40%	0%
37252		25	25						25		25		25%	25%	50%	0%
37252		20				20		20	20		20		20%	40%	20%	20%
37310		20	20						20	20	20		20%	40%	40%	0%
37313		33	33						33				33%	33%	33%	0%
37313		25				25		25	25				25%	50%	0%	25%
37371		25	25						25	25			25%	50%	25%	0%
37371		20				20		20	20	20			20%	60%	0%	20%
37375		20	20	20	20	20							20%	40%	20%	20%
37379		20		20	20		20					20	20%	20%	20%	40%
37458		20		20	20		20				20		20%	20%	40%	20%

Table A.4: Combinations of generic requirements at MS numbers in the range 20001 to 40000 (details of headings given at end of table)

MS No.	n10010	n10007	n10005	n10001	n05010	n05007	n05005	n05001	n00110	n00107	n00105	n00101	% ps10	% ps7	% ps5	% ps 1
37500		25		25	25		25						25%	25%	25%	25%
37500			20		20	20	20	20					20%	20%	40%	20%
37505			20		20			20			20	20	20%	0%	40%	40%
37505				20	20	20					20	20	20%	20%	20%	40%
37538		20		20	20		20			20			20%	40%	20%	20%
37567			25		25			25				25	25%	0%	25%	50%
37567				25	25	25						25	25%	25%	0%	50%
37624			20		20			20		20		20	20%	20%	20%	40%
37624				20	20	20				20		20	20%	40%	0%	40%
37649	10	10	10	10			10	10	10	10	10	10	20%	20%	30%	30%
37687			25		25			25			25		25%	0%	50%	25%
37687				25	25	25					25		25%	25%	25%	25%
37708		20		20	20		20		20				40%	20%	20%	20%
37743			20		20			20		20	20		20%	20%	40%	20%
37743				20	20	20				20	20		20%	40%	20%	20%
37750			33		33			33					33%	0%	33%	33%
37750				33	33	33							33%	33%	0%	33%
37750	20		20	20		20		20					20%	20%	20%	40%
37806			25		25			25		25			25%	25%	25%	25%
37806				25	25	25				25			25%	50%	0%	25%
37876			20		20			20	20			20	40%	0%	20%	40%
37876				20	20	20			20			20	40%	20%	0%	40%
37877	20			20			20	20				20	20%	0%	20%	60%
37957	20			20			20	20			20		20%	0%	40%	40%
37995			20		20			20	20		20		40%	0%	40%	20%
37995				20	20	20			20		20		40%	20%	20%	20%
38000	25			25			25	25					25%	0%	25%	50%
38037	20			20			20	20		20			20%	20%	20%	40%
38060			25		25			25	25				50%	0%	25%	25%
38060				25	25	25			25				50%	25%	0%	25%
38114			20		20			20	20	20			40%	20%	20%	20%
38114				20	20	20			20	20			40%	40%	0%	20%
38206	20			20			20	20	20				40%	0%	20%	40%
38562	10	10	10	10		10	10	10		10	10	10	10%	30%	30%	30%
38655	10	10	10	10		10	10	10	10		10	10	20%	20%	30%	30%
38698	10	10	10	10		10	10	10	10	10		10	20%	30%	20%	30%
38741	10	10	10	10		10	10	10	10	10	10		20%	30%	30%	20%
39000	20	20	20	20				20					20%	20%	20%	40%
39143		20	20		20		20	20					20%	20%	40%	20%
39143		20		20	20	20	20						20%	40%	20%	20%
39190		20	20			20					20	20	0%	40%	40%	20%
39247		25	25			25						25	0%	50%	25%	25%
39286		20	20			20				20		20	0%	60%	20%	20%

Table A.4: Combinations of generic requirements at MS numbers in the range 20001 to 40000 (details of headings given at end of table)

MS No.	n10010	n10007	n10005	n10001	n05010	n05007	n05005	n05001	n00110	n00107	n00105	n00101	% ps10	% ps7	% ps5	% ps 1
39343		25	25			25					25		0%	50%	50%	0%
39381		20	20			20				20	20		0%	60%	40%	0%
39400			25			75							0%	75%	25%	0%
39400		33	33			33							0%	67%	33%	0%
39438		25	25			25				25			0%	75%	25%	0%
39462	20		20	20			20					20	20%	0%	40%	40%
39488		20	20			20			20			20	20%	40%	20%	20%
39530	20		20	20			20				20		20%	0%	60%	20%
39571	25		25	25			25						25%	0%	50%	25%
39571	20			20		20	20	20					20%	20%	20%	40%
39583		20	20			20			20		20		20%	40%	40%	0%
39598	20		20	20			20			20			20%	20%	40%	20%
39641		25	25			25			25				25%	50%	25%	0%
39679		20	20			20			20	20			20%	60%	20%	0%
39744	20		20	20			20		20				40%	0%	40%	20%
39786		20		20	20						20	20	20%	20%	20%	40%
39845		25		25	25							25	25%	25%	0%	50%
39845			20		20	20		20				20	20%	20%	20%	40%
39881		20		20	20					20		20	20%	40%	0%	40%
39940		25		25	25						25		25%	25%	25%	25%
39940			20		20	20		20			20		20%	20%	40%	20%
39976		20		20	20					20	20		20%	40%	20%	20%
40000		33		33	33								33%	33%	0%	33%
40000			25		25	25		25					25%	25%	25%	25%

Notes:

MS No. MS number
n10010 Number of generic requirements with a weighting of 100 and product score of 10
n10007 Number of generic requirements with a weighting of 100 and product score of 7
n10005 Number of generic requirements with a weighting of 100 and product score of 5
n10001 number of generic requirements with a weighting of 100 and product score of 1
n05010 number of generic requirements with a weighting of 50 and product score of 10
n05007 number of generic requirements with a weighting of 50 and product score of 7
n05005 number of generic requirements with a weighting of 50 and product score of 5
n05001 number of generic requirements with a weighting of 50 and product score of 1
n00110 number of generic requirements with a weighting of 1 and product score of 10
n00107 number of generic requirements with a weighting of 1 and product score of 7
n00105 number of generic requirements with a weighting of 1 and product score of 5
n00101 number of generic requirements with a weighting of 1 and product score of 1

%ps10 percentage of generic requirements with a product score of 10
%ps7 percentage of generic requirements with a product score of 7
%ps5 percentage of generic requirements with a product score of 5
%ps1 percentage of generic requirements with a product score of 1

Table A.5: Combinations of generic requirements at MS numbers in the range 40001 to 60000 (details of headings given at end of table)

MS No.	n10010	n10007	n10005	n10001	n05010	n05007	n05005	n05001	n00110	n00107	n00105	n00101	% ps10	% ps7	% ps5	% ps 1
40030	10	10	10	10		10		10	10	10	10	10	20%	30%	20%	30%
40036		25		25	25					25			25%	50%	0%	25%
40036			20		20	20		20		20			20%	40%	20%	20%
40083		20		20	20				20			20	40%	20%	0%	40%
40179		20		20	20				20		20		40%	20%	20%	20%
40239		25		25	25				25				50%	25%	0%	25%
40239			20		20	20		20	20				40%	20%	20%	20%
40274		20		20	20				20	20			40%	40%	0%	20%
40381	20			20				20			20	20	20%	0%	20%	60%
40408		10	10		10	10	10	10	10	10	10	10	20%	30%	30%	20%
40442	25			25				25				25	25%	0%	0%	75%
40476	20			20				20		20		20	20%	20%	0%	60%
40538	25			25				25			25		25%	0%	25%	50%
40571	20			20				20		20	20		20%	20%	20%	40%
40600	25							75					25%	0%	0%	75%
40600	33			33				33					33%	0%	0%	67%
40632		25					25				25	25	0%	25%	50%	25%
40633	25			25				25		25			25%	25%	0%	50%
40679	20			20				20	20			20	40%	0%	0%	60%
40686		20					20			20	20	20	0%	40%	40%	20%
40735		33					33					33	0%	33%	33%	33%
40750	20	20		20			20	20					20%	20%	20%	40%
40750	20		20	20		20	20						20%	20%	40%	20%
40774	20			20				20	20		20		40%	0%	20%	40%
40789		25					25			25		25	0%	50%	25%	25%
40837	25			25				25	25				50%	0%	0%	50%
40869	20			20				20	20	20			40%	20%	0%	40%
40894		33					33				33		0%	33%	67%	0%
40947		25					25			25	25		0%	50%	50%	0%
41000		50					50						0%	50%	50%	0%
41000		25					25						0%	50%	50%	0%
41000		25					25						0%	50%	50%	0%
41020		20					20		20		20	20	20%	20%	40%	20%
41053		33					33			33			0%	67%	33%	0%
41125		25					25		25			25	25%	25%	25%	25%
41176		20					20		20	20		20	20%	40%	20%	20%
41283		25					25		25		25		25%	25%	50%	0%
41333		20					20		20	20	20		20%	40%	40%	0%
41365		20	20		20			20				20	20%	20%	20%	40%
41365		20		20	20	20						20	20%	40%	0%	40%
41391		33					33		33				33%	33%	33%	0%

Table A.5: Combinations of generic requirements at MS numbers in the range 40001 to 60000 (details of headings given at end of table)

MS No.	n10010	n10007	n10005	n10001	n05010	n05007	n05005	n05001	n00110	n00107	n00105	n00101	% ps10	% ps7	% ps5	% ps 1
41441		25					25		25	25			25%	50%	25%	0%
41445		20	20		20			20			20		20%	20%	40%	20%
41445		20		20	20	20					20		20%	40%	20%	20%
41500		25	25		25			25					25%	25%	25%	25%
41500		25		25	25	25							25%	50%	0%	25%
41525		20	20		20			20		20			20%	40%	20%	20%
41525		20		20	20	20				20			20%	60%	0%	20%
41667	20	20	20	20			20						20%	20%	40%	20%
41685	10	10		10		10	10	10	10	10	10	10	20%	30%	20%	30%
41694		20	20		20			20	20				40%	20%	20%	20%
41694		20		20	20	20			20				40%	40%	0%	20%
41808	20		20	20							20	20	20%	0%	40%	40%
41864	25		25	25								25	25%	0%	25%	50%
41864	20			20		20		20				20	20%	20%	0%	60%
41887	20		20	20						20		20	20%	20%	20%	40%
41944	25		25	25							25		25%	0%	50%	25%
41944	20			20		20		20			20		20%	20%	20%	40%
41967	20		20	20						20	20		20%	20%	40%	20%
42000	33		33	33									33%	0%	33%	33%
42000	25			25		25		25					25%	25%	0%	50%
42015	10		10	10	10		10	10	10	10	10	10	30%	10%	30%	30%
42023	25		25	25						25			25%	25%	25%	25%
42023	20			20		20		20		20			20%	40%	0%	40%
42056	20		20	20					20			20	40%	0%	20%	40%
42136	20		20	20					20		20		40%	0%	40%	20%
42143		75						25					0%	75%	0%	25%
42193	25		25	25					25				50%	0%	25%	25%
42193	20			20		20		20	20				40%	20%	0%	40%
42215	20		20	20					20	20			40%	20%	20%	20%
42411	10	10	10	10		10	10		10	10	10	10	20%	30%	30%	20%
42571		20	20		20	20		20					20%	40%	20%	20%
42594	10		10	10	10	10	10	10		10	10	10	20%	20%	30%	30%
42696	10		10	10	10	10	10	10	10		10	10	30%	10%	30%	30%
42703		20				20	20				20	20	0%	40%	40%	20%
42744	10		10	10	10	10	10	10	10	10		10	30%	20%	20%	30%
42791		25				25	25					25	0%	50%	25%	25%
42791	10		10	10	10	10	10	10	10	10	10		30%	20%	30%	20%
42822		20				20	20			20		20	0%	60%	20%	20%
42880	20	20		20				20				20	20%	20%	0%	60%
42880	20		20	20		20						20	20%	20%	20%	40%
42910		25				25	25				25		0%	50%	50%	0%
42941		20				20	20			20	20		0%	60%	40%	0%
42949	20	20		20				20			20		20%	20%	20%	40%

Table A.5: Combinations of generic requirements at MS numbers in the range 40001 to 60000 (details of headings given at end of table)

MS No.	n10010	n10007	n10005	n10001	n05010	n05007	n05005	n05001	n00110	n00107	n00105	n00101	% ps10	% ps7	% ps5	% ps 1
42949	20		20	20		20					20		20%	20%	40%	20%
43000		75	25										0%	75%	25%	0%
43000		33				33	33						0%	67%	33%	0%
43000	25	25		25				25					25%	25%	0%	50%
43000	25		25	25		25							25%	25%	25%	25%
43017	20	20		20				20		20			20%	40%	0%	40%
43017	20		20	20		20				20			20%	40%	20%	20%
43030		25				25	25			25			0%	75%	25%	0%
43074		20				20	20		20			20	20%	40%	20%	20%
43162	20	20		20				20	20				40%	20%	0%	40%
43162	20		20	20		20			20				40%	20%	20%	20%
43174	10	10	10	10	10		10	10		10	10	10	20%	20%	30%	30%
43193		20				20	20		20		20		20%	40%	40%	0%
43266	10	10	10	10	10		10	10	10		10	10	30%	10%	30%	30%
43284		25				25	25		25				25%	50%	25%	0%
43309	10	10	10	10	10		10	10	10	10		10	30%	20%	20%	30%
43312		20				20	20		20	20			20%	60%	20%	0%
43353	10	10	10	10	10		10	10	10	10	10		30%	20%	30%	20%
43446			20		20		20				20	20	20%	0%	60%	20%
43537			25		25		25					25	25%	0%	50%	25%
43564			20		20		20			20		20	20%	20%	40%	20%
43643	20	20	20	20								20	20%	20%	20%	40%
43648	10	10	10	10	10	10	10	10			10	10	20%	20%	30%	30%
43657			25		25		25				25		25%	0%	75%	0%
43683			20		20		20			20	20		20%	20%	60%	0%
43688	10	10	10	10	10	10	10	10		10		10	20%	30%	20%	30%
43703	20	20	20	20							20		20%	20%	40%	20%
43728	10	10	10	10	10	10	10	10		10	10		20%	30%	30%	20%
43750	25		75										25%	0%	75%	0%
43750			33		33		33						33%	0%	67%	0%
43750	25	25	25	25									25%	25%	25%	25%
43750	20	20		20		20		20					20%	40%	0%	40%
43763	20	20	20	20						20			20%	40%	20%	20%
43772	10	10	10	10	10	10	10	10	10			10	30%	20%	20%	30%
43776			25		25		25			25			25%	25%	50%	0%
43812	10	10	10	10	10	10	10	10	10		10		30%	20%	30%	20%
43817			20		20		20		20			20	40%	0%	40%	20%
43852	10	10	10	10	10	10	10	10	10	10			30%	30%	20%	20%
43890	20	20	20	20					20				40%	20%	20%	20%
43936			20		20		20		20		20		40%	0%	60%	0%
44030			25		25		25		25				50%	0%	50%	0%
44054			20		20		20		20	20			40%	20%	40%	0%
44125	20		20	20	20			20					40%	0%	20%	40%

Table A.5: Combinations of generic requirements at MS numbers in the range 40001 to 60000 (details of headings given at end of table)

MS No.	n10010	n10007	n10005	n10001	n05010	n05007	n05005	n05001	n00110	n00107	n00105	n00101	% ps10	% ps7	% ps5	% ps 1
44333	20	20	20	20		20							20%	40%	20%	20%
44625		20			20		20	20				20	20%	20%	20%	40%
44625			20		20	20	20					20	20%	20%	40%	20%
44659	10		10	10	10	10		10	10	10	10	10	30%	20%	20%	30%
44721		20			20		20	20			20		20%	20%	40%	20%
44721			20		20	20	20				20		20%	20%	60%	0%
44800		25			25		25	25					25%	25%	25%	25%
44800			25		25	25	25						25%	25%	50%	0%
44817		20			20		20	20		20			20%	40%	20%	20%
44817			20		20	20	20			20			20%	40%	40%	0%
45020		20			20		20	20	20				40%	20%	20%	20%
45020			20		20	20	20		20				40%	20%	40%	0%
45089	10	10	10	10	10			10	10	10	10	10	30%	20%	20%	30%
45143	20			20			20				20	20	20%	0%	40%	40%
45223	25			25			25					25	25%	0%	25%	50%
45238	20			20			20			20		20	20%	20%	20%	40%
45319	25			25			25				25		25%	0%	50%	25%
45333	20			20			20			20	20		20%	20%	40%	20%
45344	10	10	10	10	10	10		10		10	10	10	20%	30%	20%	30%
45352		20	20		20		20					20	20%	20%	40%	20%
45400	33			33			33						33%	0%	33%	33%
45414	25			25			25			25			25%	25%	25%	25%
45432		20	20		20		20				20		20%	20%	60%	0%
45436	10	10	10	10	10	10		10	10		10	10	30%	20%	20%	30%
45440	20			20			20		20			20	40%	0%	20%	40%
45479	10	10	10	10	10	10		10	10	10		10	30%	30%	10%	30%
45500		25	25		25		25						25%	25%	50%	0%
45500		20			20	20	20	20					20%	40%	20%	20%
45512		20	20		20		20			20			20%	40%	40%	0%
45523	10	10	10	10	10	10		10	10	10	10		30%	30%	20%	20%
45536	20			20			20		20		20		40%	0%	40%	20%
45571		75					25						0%	75%	25%	0%
45618	25			25			25		25				50%	0%	25%	25%
45631	20			20			20		20	20			40%	20%	20%	20%
45681		20	20		20		20		20				40%	20%	40%	0%
45850	20		20				20	20				20	20%	0%	40%	40%
45850	20			20		20	20					20	20%	20%	20%	40%
45930	20		20				20	20			20		20%	0%	60%	20%
45930	20			20		20	20				20		20%	20%	40%	20%
46000	25		25				25	25					25%	0%	50%	25%
46000	25			25		25	25						25%	25%	25%	25%
46000		20	20		20	20	20						20%	40%	40%	0%
46010	20		20				20	20		20			20%	20%	40%	20%

Table A.5: Combinations of generic requirements at MS numbers in the range 40001 to 60000 (details of headings given at end of table)

MS No.	n10010	n10007	n10005	n10001	n05010	n05007	n05005	n05001	n00110	n00107	n00105	n00101	% ps10	% ps7	% ps5	% ps 1
46010	20			20		20	20			20			20%	40%	20%	20%
46179	20		20				20	20	20				40%	0%	40%	20%
46179	20			20		20	20		20				40%	20%	20%	20%
46299	20	20		20			20					20	20%	20%	20%	40%
46368	20	20		20			20				20		20%	20%	40%	20%
46429	25	25		25			25						25%	25%	25%	25%
46429	20		20			20	20	20					20%	20%	40%	20%
46436	20	20		20			20			20			20%	40%	20%	20%
46491	20	20		20			20		10	5	5		30%	25%	25%	20%
46581	20	20		20			20		20				40%	20%	20%	20%
46750	20	20	20				20	20					20%	20%	40%	20%
46750	20	20		20		20	20						20%	40%	20%	20%
46857	20			20	20		20	20					40%	0%	20%	40%
46971	10	10	10			10	10	10	10	10	10	10	20%	30%	30%	20%
47092	10			10	10	10	10	10	10	10	10	10	30%	20%	20%	30%
47125	20		20	20	20		20						40%	0%	40%	20%
47302	10	10		10	10		10	10	10	10	10	10	30%	20%	20%	30%
47302	10		10	10	10	10	10		10	10	10	10	30%	20%	30%	20%
47366	10	10		10	10	10	10	10		10	10	10	20%	30%	20%	30%
47467	10	10		10	10	10	10	10	10		10	10	30%	20%	20%	30%
47470	10	10	10	10	10		10		10	10	10	10	30%	20%	30%	20%
47514	10	10	10	10	10	10	10			10	10	10	20%	30%	30%	20%
47515	10	10		10	10	10	10	10	10	10		10	30%	30%	10%	30%
47563	10	10		10	10	10	10	10	10	10	10		30%	30%	20%	20%
47602		25										75	0%	25%	0%	75%
47606	10	10	10	10	10	10	10		10		10	10	30%	20%	30%	20%
47649	10	10	10	10	10	10	10		10	10		10	30%	30%	20%	20%
47693	10	10	10	10	10	10	10		10	10	10		30%	30%	30%	10%
48294		33									33	33	0%	33%	33%	33%
48301		25									75		0%	25%	75%	0%
48301		25								25	25	25	0%	50%	25%	25%
48525		50										50	0%	50%	0%	50%
48525		25										25	0%	50%	0%	50%
48525		25										25	0%	50%	0%	50%
48526		25				25					25	25	0%	50%	25%	25%
48529		33								33		33	0%	67%	0%	33%
48529		20				20				20	20	20	0%	60%	20%	20%
48682		33				33						33	0%	67%	0%	33%
48684		25				25				25		25	0%	75%	0%	25%
48762		50									50		0%	50%	50%	0%
48762		25									25		0%	50%	50%	0%
48762		25									25		0%	50%	50%	0%
48765		33								33	33		0%	67%	33%	0%

Table A.5: Combinations of generic requirements at MS numbers in the range 40001 to 60000 (details of headings given at end of table)

MS No.	n10010	n10007	n10005	n10001	n05010	n05007	n05005	n05001	n00110	n00107	n00105	n00101	% ps10	% ps7	% ps5	% ps 1
48796		25							25		25	25	25%	25%	25%	25%
48798		20							20	20	20	20	20%	40%	20%	20%
48841		75										25	0%	75%	0%	25%
48841		33				33					33		0%	67%	33%	0%
48842		25				25				25	25		0%	75%	25%	0%
48863		20				20			20		20	20	20%	40%	20%	20%
48920		75									25		0%	75%	25%	0%
49000		100											0%	100%	0%	0%
49000		50				50							0%	100%	0%	0%
49000		50								50			0%	100%	0%	0%
49000		25				25							0%	100%	0%	0%
49000		25								25			0%	100%	0%	0%
49000		75				75							0%	100%	0%	0%
49000		75								75			0%	100%	0%	0%
49000		25				25							0%	100%	0%	0%
49000		25								25			0%	100%	0%	0%
49000		25				25							0%	100%	0%	0%
49000		25								25			0%	100%	0%	0%
49000		33				33				33			0%	100%	0%	0%
49020		20				20			20	20		20	20%	60%	0%	20%
49020		25				25			25			25	25%	50%	0%	25%
49029		25							25	25		25	25%	50%	0%	25%
49029		33							33			33	33%	33%	0%	33%
49169		75							25				25%	75%	0%	0%
49176		20				20			20	20	20		20%	60%	20%	0%
49178		25				25			25		25		25%	50%	25%	0%
49262		25							25	25	25		25%	50%	25%	0%
49265		33							33		33		33%	33%	33%	0%
49310		20	20		20						20	20	20%	20%	40%	20%
49336		25				25			25	25			25%	75%	0%	0%
49338		33				33			33				33%	67%	0%	0%
49339		20	20		20	20						20	20%	40%	20%	20%
49386		20			20			20			20	20	20%	20%	20%	40%
49386			20		20	20					20	20	20%	20%	40%	20%
49405		20	20		20					20		20	20%	40%	20%	20%
49406		25	25		25							25	25%	25%	25%	25%
49406		20			20	20		20				20	20%	40%	0%	40%
49419		20	20		20	20					20		20%	40%	40%	0%
49498		20	20		20	20				20			20%	60%	20%	0%
49500		33							33	33			33%	67%	0%	0%
49500		25	25		25	25							25%	50%	25%	0%
49500		20	20		20					20	20		20%	40%	40%	0%
49502		25	25		25						25		25%	25%	50%	0%

Table A.5: Combinations of generic requirements at MS numbers in the range 40001 to 60000 (details of headings given at end of table)

MS No.	n10010	n10007	n10005	n10001	n05010	n05007	n05005	n05001	n00110	n00107	n00105	n00101	% ps10	% ps7	% ps5	% ps 1
49502		20			20	20		20			20		20%	40%	20%	20%
49505		50							50				50%	50%	0%	0%
49505		25							25				50%	50%	0%	0%
49505		25							25				50%	50%	0%	0%
49505		20			20			20		20		20	20%	40%	0%	40%
49505			20		20	20				20		20	20%	40%	20%	20%
49507		25			25			25				25	25%	25%	0%	50%
49507			25		25	25						25	25%	25%	25%	25%
49510			20		20					20	20	20	20%	20%	40%	20%
49513			25		25						25	25	25%	0%	50%	25%
49598		25	25		25					25			25%	50%	25%	0%
49598		20			20	20		20		20			20%	60%	0%	20%
49600		33	33		33								33%	33%	33%	0%
49600		25			25	25		25					25%	50%	0%	25%
49607		20	20		20				20			20	40%	20%	20%	20%
49624		20			20			20		20	20		20%	40%	20%	20%
49624			20		20	20				20	20		20%	40%	40%	0%
49627		25			25			25			25		25%	25%	25%	25%
49627			25		25	25					25		25%	25%	50%	0%
49668		20	20		20	20			20				40%	40%	20%	0%
49671			25		25					25		25	25%	25%	25%	25%
49675			33		33							33	33%	0%	33%	33%
49702		20	20		20				20		20		40%	20%	40%	0%
49718	20	20	20					20				20	20%	20%	20%	40%
49718	20	20		20		20						20	20%	40%	0%	40%
49746		25			25			25		25			25%	50%	0%	25%
49746			25		25	25				25			25%	50%	25%	0%
49750		33			33			33					33%	33%	0%	33%
49750			33		33	33							33%	33%	33%	0%
49750	20	20	20			20		20					20%	40%	20%	20%
49755	20	20		20							20	20	20%	20%	20%	40%
49757		20			20			20	20			20	40%	20%	0%	40%
49757			20		20	20			20			20	40%	20%	20%	20%
49786	20	20	20					20			20		20%	20%	40%	20%
49786	20	20		20		20					20		20%	40%	20%	20%
49798		20	20		20				20	20			40%	40%	20%	0%
49801		25	25		25				25				50%	25%	25%	0%
49801		20			20	20		20	20				40%	40%	0%	20%
49829			25		25					25	25		25%	25%	50%	0%
49834			33		33						33		33%	0%	67%	0%
49834	20	20		20						20		20	20%	40%	0%	40%
49837	25	25		25								25	25%	25%	0%	50%
49837	20		20			20		20				20	20%	20%	20%	40%

Table A.5: Combinations of generic requirements at MS numbers in the range 40001 to 60000 (details of headings given at end of table)

MS No.	n10010	n10007	n10005	n10001	n05010	n05007	n05005	n05001	n00110	n00107	n00105	n00101	% ps10	% ps7	% ps5	% ps 1
49843			20		20				20		20	20	40%	0%	40%	20%
49851	10	10	10	10	10	10			10	10	10	10	30%	30%	20%	20%
49855	20	20	20					20		20			20%	40%	20%	20%
49855	20	20		20		20				20			20%	60%	0%	20%
49857	25	25	25					25					25%	25%	25%	25%
49857	25	25		25		25							25%	50%	0%	25%
49876		20			20			20	20		20		40%	20%	20%	20%
49876			20		20	20			20		20		40%	20%	40%	0%
49905	20		20					20			20	20	20%	0%	40%	40%
49905	20			20		20					20	20	20%	20%	20%	40%
49914	20	20		20						20	20		20%	40%	20%	20%
49917	25	25		25							25		25%	25%	25%	25%
49917	20		20			20		20			20		20%	20%	40%	20%
49945	10	10		10	10	10		10	10	10	10	10	30%	30%	10%	30%
49993			33		33					33			33%	33%	33%	0%
49995		20			20			20	20	20			40%	40%	0%	20%
49995			20		20	20			20	20			40%	40%	20%	0%
49997	25	25		25						25			25%	50%	0%	25%
49997	20		20			20		20		20			20%	40%	20%	20%
50000			50		50								50%	0%	50%	0%
50000			25		25								50%	0%	50%	0%
50000			25		25								50%	0%	50%	0%
50000	33	33		33									33%	33%	0%	33%
50000	25		25			25		25					25%	25%	25%	25%
50000		25			25			25	25				50%	25%	0%	25%
50000			25		25	25			25				50%	25%	25%	0%
50000	20	20	20	20	20								40%	20%	20%	20%
50000	20	20	20					20	20				40%	20%	20%	20%
50000	20	20		20		20			20				40%	40%	0%	20%
50000	20		20					20		20		20	20%	20%	20%	40%
50000	20			20		20				20		20	20%	40%	0%	40%
50000			20		20				20	20		20	40%	20%	20%	20%
50003	20	20		20					20			20	40%	20%	0%	40%
50004	25		25					25				25	25%	0%	25%	50%
50004	25			25		25						25	25%	25%	0%	50%
50007			25		25				25			25	50%	0%	25%	25%
50083	20	20		20					20		20		40%	20%	20%	20%
50095	20		20					20		20	20		20%	20%	40%	20%
50095	20			20		20				20	20		20%	40%	20%	20%
50100	25		25					25			25		25%	0%	50%	25%
50100	25			25		25					25		25%	25%	25%	25%
50123	20			20						20	20	20	20%	20%	20%	40%
50125	20	20		20	20			20					40%	20%	0%	40%

Table A.5: Combinations of generic requirements at MS numbers in the range 40001 to 60000 (details of headings given at end of table)

MS No.	n10010	n10007	n10005	n10001	n05010	n05007	n05005	n05001	n00110	n00107	n00105	n00101	% ps10	% ps7	% ps5	% ps 1
50125	20		20	20	20	20							40%	20%	20%	20%
50129	25			25							25	25	25%	0%	25%	50%
50145	20		20	20	20							20	40%	0%	20%	40%
50157			20		20				20	20	20		40%	20%	40%	0%
50162	20	20		20					20	20			40%	40%	0%	20%
50164			25		25				25		25		50%	0%	50%	0%
50166	25	25		25					25				50%	25%	0%	25%
50166	20		20			20		20	20				40%	20%	20%	20%
50195	25		25					25		25			25%	25%	25%	25%
50195	25			25		25				25			25%	50%	0%	25%
50200	33		33					33					33%	0%	33%	33%
50200	33			33		33							33%	33%	0%	33%
50202	20		20					20	20			20	40%	0%	20%	40%
50202	20			20		20			20			20	40%	20%	0%	40%
50214	20		20	20	20						20		40%	0%	40%	20%
50248	25			25						25		25	25%	25%	0%	50%
50254	33			33								33	33%	0%	0%	67%
50282	20		20	20	20					20			40%	20%	20%	20%
50286	25		25	25	25								50%	0%	25%	25%
50286	20			20	20	20		20					40%	20%	0%	40%
50298	20		20					20	20		20		40%	0%	40%	20%
50298	20			20		20			20		20		40%	20%	20%	20%
50322			25		25				25	25			50%	25%	25%	0%
50331			33		33				33				67%	0%	33%	0%
50336	20			20	20			20				20	40%	0%	0%	60%
50366	25			25						25	25		25%	25%	25%	25%
50373	33			33							33		33%	0%	33%	33%
50374	20			20					20		20	20	40%	0%	20%	40%
50393	20		20					20	20	20			40%	20%	20%	20%
50393	20			20		20			20	20			40%	40%	0%	20%
50398	25		25					25	25				50%	0%	25%	25%
50398	25			25		25			25				50%	25%	0%	25%
50415	20			20	20			20			20		40%	0%	20%	40%
50427	20		20	20	20				20				60%	0%	20%	20%
50485		25							75				75%	25%	0%	0%
50493	33			33						33			33%	33%	0%	33%
50493	20			20					20	20		20	40%	20%	0%	40%
50495	20			20	20			20		20			40%	20%	0%	40%
50500	50			50									50%	0%	0%	50%
50500	25			25									50%	0%	0%	50%
50500	25			25									50%	0%	0%	50%
50500	25			25	25			25					50%	0%	0%	50%
50500	25			25					25			25	50%	0%	0%	50%

Table A.5: Combinations of generic requirements at MS numbers in the range 40001 to 60000 (details of headings given at end of table)

MS No.	n10010	n10007	n10005	n10001	n05010	n05007	n05005	n05001	n00110	n00107	n00105	n00101	% ps10	% ps7	% ps5	% ps 1
50611	20			20					20	20	20		40%	20%	20%	20%
50619	25			25					25		25		50%	0%	25%	25%
50664	20			20	20			20	20				60%	0%	0%	40%
50738	25			25					25	25			50%	25%	0%	25%
50746	33			33					33				67%	0%	0%	33%
52137	10	10	10		10	10	10	10		10	10	10	20%	30%	30%	20%
52239	10	10	10		10	10	10	10	10		10	10	30%	20%	30%	20%
52286	10	10	10		10	10	10	10	10	10		10	30%	30%	20%	20%
52334	10	10	10		10	10	10	10	10	10	10		30%	30%	30%	10%
52588	10	10	10		10		10	10	10	10	10	10	30%	20%	30%	20%
52588	10	10		10	10	10	10		10	10	10	10	30%	30%	20%	20%
52750	20	20	20			20	20						20%	40%	40%	0%
53032	10		10		10	10	10	10	10	10	10	10	30%	20%	30%	20%
53125	20	20		20	20		20						40%	20%	20%	20%
53137	20	20	20				20					20	20%	20%	40%	20%
53205	20	20	20				20				20		20%	20%	60%	0%
53274	20	20	20				20			20			20%	40%	40%	0%
53286	25	25	25				25						25%	25%	50%	0%
53286	20	20				20	20	20					20%	40%	20%	20%
53419	20	20	20				20		20				40%	20%	40%	0%
53477	15	20	5	5	5		5	10	30	5			50%	25%	10%	15%
53523	15	20	5	5	5		5	10	35				55%	20%	10%	15%
53714	20		20		20		20	20					40%	0%	40%	20%
53714	20			20	20	20	20						40%	20%	20%	20%
53824	20	20					20	20				20	20%	20%	20%	40%
53824	20		20			20	20					20	20%	20%	40%	20%
53904	20	20					20	20			20		20%	20%	40%	20%
53904	20		20			20	20				20		20%	20%	60%	0%
53983	20	20					20	20		20			20%	40%	20%	20%
53983	20		20			20	20			20			20%	40%	40%	0%
54000	25	25					25	25					25%	25%	25%	25%
54000	25		25			25	25						25%	25%	50%	0%
54153	20	20					20	20	20				40%	20%	20%	20%
54153	20		20			20	20		20				40%	20%	40%	0%
54187		20			20	20	20					20	20%	40%	20%	20%
54283		20			20	20	20				20		20%	40%	40%	0%
54322	20			20	20		20					20	40%	0%	20%	40%
54378		20			20	20	20			20			20%	60%	20%	0%
54400		25			25	25	25						25%	50%	25%	0%
54402	20			20	20		20				20		40%	0%	40%	20%
54482	20			20	20		20			20			40%	20%	20%	20%
54500	25			25	25		25						50%	0%	25%	25%
54582		20			20	20	20		20				40%	40%	20%	0%

Table A.5: Combinations of generic requirements at MS numbers in the range 40001 to 60000 (details of headings given at end of table)

MS No.	n10010	n10007	n10005	n10001	n05010	n05007	n05005	n05001	n00110	n00107	n00105	n00101	% ps10	% ps7	% ps5	% ps 1
54651	20			20	20		20		20				60%	0%	20%	20%
54667	20		20				20				20	20	20%	0%	60%	20%
54762	20		20				20			20		20	20%	20%	40%	20%
54785	25		25				25					25	25%	0%	50%	25%
54785	20					20	20	20				20	20%	20%	20%	40%
54857	20		20				20			20	20		20%	20%	60%	0%
54880	25		25				25				25		25%	0%	75%	0%
54880	20					20	20	20			20		20%	20%	40%	20%
54964	20		20				20		20			20	40%	0%	40%	20%
54976	25		25				25			25			25%	25%	50%	0%
54976	20					20	20	20		20			20%	40%	20%	20%
55000	25						75						25%	0%	75%	0%
55000	33		33				33						33%	0%	67%	0%
55000	25					25	25	25					25%	25%	25%	25%
55060	20		20				20		20		20		40%	0%	60%	0%
55155	20		20				20		20	20			40%	20%	40%	0%
55179	25		25				25		25				50%	0%	50%	0%
55179	20					20	20	20	20				40%	20%	20%	20%
55231	10	10	10		10	10		10	10	10	10	10	30%	30%	20%	20%
55327		20			20		20				20	20	20%	20%	40%	20%
55446		20			20		20			20		20	20%	40%	20%	20%
55478		25			25		25					25	25%	25%	25%	25%
55564		20			20		20			20	20		20%	40%	40%	0%
55597		25			25		25				25		25%	25%	50%	0%
55698		20			20		20		20			20	40%	20%	20%	20%
55716		25			25		25			25			25%	50%	25%	0%
55750		33			33		33						33%	33%	33%	0%
55817		20			20		20		20		20		40%	20%	40%	0%
55936		20			20		20		20	20			40%	40%	20%	0%
55970		25			25		25		25				50%	25%	25%	0%
56069	20						20	20			20	20	20%	0%	40%	40%
56125	20	20	20		20			20					40%	20%	20%	20%
56125	20	20		20	20	20							40%	40%	0%	20%
56188	20						20	20		20		20	20%	20%	20%	40%
56224	25						25	25				25	25%	0%	25%	50%
56286		75			25								25%	75%	0%	0%
56307	20						20	20		20	20		20%	20%	40%	20%
56343	25						25	25			25		25%	0%	50%	25%
56441	20						20	20	20			20	40%	0%	20%	40%
56463	25						25	25		25			25%	25%	25%	25%
56500	33						33	33					33%	0%	33%	33%
56556	20	20	20			20						20	20%	40%	20%	20%
56559	20						20	20	20		20		40%	0%	40%	20%

Table A.5: Combinations of generic requirements at MS numbers in the range 40001 to 60000 (details of headings given at end of table)

MS No.	n10010	n10007	n10005	n10001	n05010	n05007	n05005	n05001	n00110	n00107	n00105	n00101	% ps10	% ps7	% ps5	% ps 1
56624	20	20	20			20					20		20%	40%	40%	0%
56678	20						20	20	20	20			40%	20%	20%	20%
56692	20	20	20			20				20			20%	60%	20%	0%
56714	25	25	25			25							25%	50%	25%	0%
56716	25						25	25	25				50%	0%	25%	25%
56838	20	20	20			20			20				40%	40%	20%	0%
56983	20	20		20	20							20	40%	20%	0%	40%
57051	20	20		20	20						20		40%	20%	20%	20%
57120	20	20		20	20					20			40%	40%	0%	20%
57143	25	25		25	25								50%	25%	0%	25%
57143	20		20		20	20		20					40%	20%	20%	20%
57265	20	20		20	20				20				60%	20%	0%	20%
57702	20	20	20								20	20	20%	20%	40%	20%
57781	20	20	20							20		20	20%	40%	20%	20%
57811	25	25	25									25	25%	25%	25%	25%
57811	20	20				20		20				20	20%	40%	0%	40%
57861	20	20	20							20	20		20%	40%	40%	0%
57874	10	10	10		10	10	10		10	10	10	10	30%	30%	30%	10%
57890	25	25	25								25		25%	25%	50%	0%
57890	20	20				20		20			20		20%	40%	20%	20%
57950	20	20	20						20			20	40%	20%	20%	20%
57970	25	25	25							25			25%	50%	25%	0%
57970	20	20				20		20		20			20%	60%	0%	20%
58000	33	33	33										33%	33%	33%	0%
58000	25	25				25		25					25%	50%	0%	25%
58030	20	20	20						20		20		40%	20%	40%	0%
58109	20	20	20						20	20			40%	40%	20%	0%
58140	25	25	25						25				50%	25%	25%	0%
58140	20	20				20		20	20				40%	40%	0%	20%
58309	20		20		20			20				20	40%	0%	20%	40%
58309	20			20	20	20						20	40%	20%	0%	40%
58389	20		20		20			20			20		40%	0%	40%	20%
58389	20			20	20	20					20		40%	20%	20%	20%
58468	20		20		20			20		20			40%	20%	20%	20%
58468	20			20	20	20				20			40%	40%	0%	20%
58500	25		25		25			25					50%	0%	25%	25%
58500	25			25	25	25							50%	25%	0%	25%
58638	20		20		20			20	20				60%	0%	20%	20%
58638	20			20	20	20			20				60%	20%	0%	20%
58973	10	10			10	10	10	10	10	10	10	10	30%	30%	20%	20%
59125	20	20	20		20		20						40%	20%	40%	0%
59429	20	20						20			20	20	20%	20%	20%	40%
59429	20		20			20					20	20	20%	20%	40%	20%

Table A.5: Combinations of generic requirements at MS numbers in the range 40001 to 60000 (details of headings given at end of table)

MS No.	n10010	n10007	n10005	n10001	n05010	n05007	n05005	n05001	n00110	n00107	n00105	n00101	% ps10	% ps7	% ps5	% ps 1
59524	20	20						20		20		20	20%	40%	0%	40%
59524	20		20			20				20		20	20%	40%	20%	20%
59566	25	25						25				25	25%	25%	0%	50%
59566	25		25			25						25	25%	25%	25%	25%
59619	20	20						20		20	20		20%	40%	20%	20%
59619	20		20			20				20	20		20%	40%	40%	0%
59661	25	25						25			25		25%	25%	25%	25%
59661	25		25			25					25		25%	25%	50%	0%
59726	20	20						20	20			20	40%	20%	0%	40%
59726	20		20			20			20			20	40%	20%	20%	20%
59757	25	25						25		25			25%	50%	0%	25%
59757	25		25			25				25			25%	50%	25%	0%
59800	33	33						33					33%	33%	0%	33%
59800	33		33			33							33%	33%	33%	0%
59821	20	20						20	20		20		40%	20%	20%	20%
59821	20		20			20			20		20		40%	20%	40%	0%
59917	20	20						20	20	20			40%	40%	0%	20%
59917	20		20			20			20	20			40%	40%	20%	0%
59960	25	25						25	25				50%	25%	0%	25%
59960	25		25			25			25				50%	25%	25%	0%

Notes:

MS No.	MS number
n10010	Number of generic requirements with a weighting of 100 and product score of 10
n10007	Number of generic requirements with a weighting of 100 and product score of 7
n10005	Number of generic requirements with a weighting of 100 and product score of 5
n10001	number of generic requirements with a weighting of 100 and product score of 1
n05010	number of generic requirements with a weighting of 50 and product score of 10
n05007	number of generic requirements with a weighting of 50 and product score of 7
n05005	number of generic requirements with a weighting of 50 and product score of 5
n05001	number of generic requirements with a weighting of 50 and product score of 1
n00110	number of generic requirements with a weighting of 1 and product score of 10
n00107	number of generic requirements with a weighting of 1 and product score of 7
n00105	number of generic requirements with a weighting of 1 and product score of 5
n00101	number of generic requirements with a weighting of 1 and product score of 1
%ps10	percentage of generic requirements with a product score of 10
%ps7	percentage of generic requirements with a product score of 7
%ps5	percentage of generic requirements with a product score of 5
%ps1	percentage of generic requirements with a product score of 1

Table A.6: Combinations of generic requirements at MS numbers in the range 60001 to 80000 (details of headings given at end of table)

MS No.	n10010	n10007	n10005	n10001	n05010	n05007	n05005	n05001	n00110	n00107	n00105	n00101	% ps10	% ps7	% ps5	% ps 1
60024	20			20	20						20	20	40%	0%	20%	40%
60119	20			20	20					20		20	40%	20%	0%	40%
60163	25			25	25							25	50%	0%	0%	50%
60214	20			20	20					20	20		40%	20%	20%	20%
60259	25			25	25						25		50%	0%	25%	25%
60321	20			20	20				20			20	60%	0%	0%	40%
60355	25			25	25					25			50%	25%	0%	25%
60400				25	75								75%	0%	0%	25%
60400	33			33	33								67%	0%	0%	33%
60417	20			20	20				20		20		60%	0%	20%	20%
60512	20			20	20				20	20			60%	20%	0%	20%
60558	25			25	25				25				75%	0%	0%	25%
60571	20	20			20		20	20					40%	20%	20%	20%
60571	20		20		20	20	20						40%	20%	40%	0%
61149		20			20	20						40	20%	40%	0%	40%
61267		20			20	20					20	20	20%	40%	20%	20%
61386		20			20	20				20		20	20%	60%	0%	20%
61448		25			25	25						25	25%	50%	0%	25%
61505		20			20	20				20	20		20%	60%	20%	0%
61567		25			25	25					25		25%	50%	25%	0%
61639		20			20	20			20			20	40%	40%	0%	20%
61687		25			25	25				25			25%	75%	0%	0%
61750	25	75											25%	75%	0%	0%
61750		33			33	33							33%	67%	0%	0%
61757		20			20	20			20		20		40%	40%	20%	0%
61797	20	20				20	20					20	20%	40%	20%	20%
61876		20			20	20			20	20			40%	60%	0%	0%
61877	20	20				20	20				20		20%	40%	40%	0%
61940		25			25	25			25				50%	50%	0%	0%
61946	20		20							20	20	20	20%	20%	40%	20%
61957	20	20				20	20			20			20%	60%	20%	0%
62000	25	25				25	25						25%	50%	25%	0%
62010	25		25								25	25	25%	0%	50%	25%
62010	20					20		20			20	20	20%	20%	20%	40%
62125	20	20	20		20	20							40%	40%	20%	0%
62126	20	20				20	20		20				40%	40%	20%	0%
62129	25		25							25		25	25%	25%	25%	25%
62129	20					20		20		20		20	20%	40%	0%	40%
62194	33		33									33	33%	0%	33%	33%
62194	25					25		25				25	25%	25%	0%	50%
62197	20		20						20		20	20	40%	0%	40%	20%
62248	25		25							25	25		25%	25%	50%	0%
62248	20					20		20		20	20		20%	40%	20%	20%

Table A.6: Combinations of generic requirements at MS numbers in the range 60001 to 80000 (details of headings given at end of table)

MS No.	n10010	n10007	n10005	n10001	n05010	n05007	n05005	n05001	n00110	n00107	n00105	n00101	% ps10	% ps7	% ps5	% ps 1
62296	20		20		20		20					20	40%	0%	40%	20%
62313	33		33								33		33%	0%	67%	0%
62313	25					25		25			25		25%	25%	25%	25%
62315	20		20						20	20		20	40%	20%	20%	20%
62375	20		20		20		20				20		40%	0%	60%	0%
62381	25		25						25			25	50%	0%	25%	25%
62381	20					20		20	20			20	40%	20%	0%	40%
62433	33		33							33			33%	33%	33%	0%
62433	25					25		25		25			25%	50%	0%	25%
62433	20		20						20	20	20		40%	20%	40%	0%
62455	20		20		20		20			20			40%	20%	40%	0%
62500	50		50										50%	0%	50%	0%
62500	25		25										50%	0%	50%	0%
62500	25		25										50%	0%	50%	0%
62500	33					33		33					33%	33%	0%	33%
62500	25		25		25		25						50%	0%	50%	0%
62500	25		25						25		25		50%	0%	50%	0%
62500	20				20	20	20	20					40%	20%	20%	20%
62500	20					20		20	20		20		40%	20%	20%	20%
62619	25		25						25	25			50%	25%	25%	0%
62619	20					20		20	20	20			40%	40%	0%	20%
62625	20		20		20		20		20				60%	0%	40%	0%
62687	33		33						33				67%	0%	33%	0%
62687	25					25		25	25				50%	25%	0%	25%
62959	30	5	20			40						5	30%	45%	20%	5%
63821	20	20	20		20							20	40%	20%	20%	20%
63889	20	20	20		20						20		40%	20%	40%	0%
63957	20	20	20		20					20			40%	40%	20%	0%
64000	25	25	25		25								50%	25%	25%	0%
64000	20	20			20	20		20					40%	40%	0%	20%
64103	20	20	20		20				20				60%	20%	20%	0%
64190	20	20					20				20	20	20%	20%	40%	20%
64286	20	20					20			20		20	20%	40%	20%	20%
64347	25	25					25					25	25%	25%	25%	25%
64381	20	20					20			20	20		20%	40%	40%	0%
64442	25	25					25				25		25%	25%	50%	0%
64488	20	20					20		20			20	40%	20%	20%	20%
64538	25	25					25			25			25%	50%	25%	0%
64583	20	20					20		20		20		40%	20%	40%	0%
64600	33	33					33						33%	33%	33%	0%
64679	20	20					20		20	20			40%	40%	20%	0%
64741	25	25					25		25				50%	25%	25%	0%
64944	20				20		20	20				20	40%	0%	20%	40%

Table A.6: Combinations of generic requirements at MS numbers in the range 60001 to 80000 (details of headings given at end of table)

MS No.	n10010	n10007	n10005	n10001	n05010	n05007	n05005	n05001	n00110	n00107	n00105	n00101	% ps10	% ps7	% ps5	% ps 1
65040	20				20		20	20			20		40%	0%	40%	20%
65135	20				20		20	20		20			40%	20%	20%	20%
65196		20			20					20	20	20	20%	40%	20%	20%
65200	25				25		25	25					50%	0%	25%	25%
65303		25			25						25	25	25%	25%	25%	25%
65339	20				20		20	20	20				60%	0%	20%	20%
65461		25			25					25		25	25%	50%	0%	25%
65529		20			20				20		20	20	40%	20%	20%	20%
65570		33			33							33	33%	33%	0%	33%
65618		25			25					25	25		25%	50%	25%	0%
65686		20			20				20	20		20	40%	40%	0%	20%
65728		33			33						33		33%	33%	33%	0%
65796		25			25				25			25	50%	25%	0%	25%
65843		20			20				20	20	20		40%	40%	20%	0%
65887		33			33					33			33%	67%	0%	0%
65954		25			25				25		25		50%	25%	25%	0%
66000		50			50								50%	50%	0%	0%
66000		25			25								50%	50%	0%	0%
66000		25			25								50%	50%	0%	0%
66112		25			25				25	25			50%	50%	0%	0%
66176	20							20		20	20	20	20%	20%	20%	40%
66225		33			33				33				67%	33%	0%	0%
66282	20	20			20			20				20	40%	20%	0%	40%
66282	20		20		20	20						20	40%	20%	20%	20%
66289	25							25			25	25	25%	0%	25%	50%
66362	20	20			20			20			20		40%	20%	20%	20%
66362	20		20		20	20					20		40%	20%	40%	0%
66442	20	20			20			20		20			40%	40%	0%	20%
66442	20		20		20	20				20			40%	40%	20%	0%
66447	25							25		25		25	25%	25%	0%	50%
66500	25	25			25			25					50%	25%	0%	25%
66500	25		25		25	25							50%	25%	25%	0%
66510	20							20	20		20	20	40%	0%	20%	40%
66563	33							33				33	33%	0%	0%	67%
66605	25							25		25	25		25%	25%	25%	25%
66611	20	20			20			20	20				60%	20%	0%	20%
66611	20		20		20	20			20				60%	20%	20%	0%
66667	20							20	20	20		20	40%	20%	0%	40%
66722	33							33			33		33%	0%	33%	33%
66783	25							25	25			25	50%	0%	0%	50%
66824	20							20	20	20	20		40%	20%	20%	20%
66881	33							33		33			33%	33%	0%	33%
66941	25							25	25		25		50%	0%	25%	25%

Table A.6: Combinations of generic requirements at MS numbers in the range 60001 to 80000 (details of headings given at end of table)

MS No.	n10010	n10007	n10005	n10001	n05010	n05007	n05005	n05001	n00110	n00107	n00105	n00101	% ps10	% ps7	% ps5	% ps 1
67000	50							50					50%	0%	0%	50%
67000	25							25					50%	0%	0%	50%
67000	25							25					50%	0%	0%	50%
67099	25							25	25	25			50%	25%	0%	25%
67219	33							33	33				67%	0%	0%	33%
67429	20	20			20	20	20						40%	40%	20%	0%
67950	20					20	20				20	20	20%	20%	40%	20%
68069	20					20	20			20		20	20%	40%	20%	20%
68164	25					25	25					25	25%	25%	25%	25%
68188	20					20	20			20	20		20%	40%	40%	0%
68284	25					25	25				25		25%	25%	50%	0%
68322	20					20	20		20			20	40%	20%	20%	20%
68403	25					25	25			25			25%	50%	25%	0%
68441	20					20	20		20		20		40%	20%	40%	0%
68500	33					33	33						33%	33%	33%	0%
68559	20					20	20		20	20			40%	40%	20%	0%
68657	25					25	25		25				50%	25%	25%	0%
68952	20	20				20					20	20	20%	40%	20%	20%
69048	20	20				20				20		20	20%	60%	0%	20%
69127	25	25				25						25	25%	50%	0%	25%
69143	20	20				20				20	20		20%	60%	20%	0%
69223	25	25				25					25		25%	50%	25%	0%
69250	20	20				20			20			20	40%	40%	0%	20%
69319	25	25				25				25			25%	75%	0%	0%
69345	20	20				20			20		20		40%	40%	20%	0%
69400	25					75							25%	75%	0%	0%
69400	33	33				33							33%	67%	0%	0%
69440	20	20				20			20	20			40%	60%	0%	0%
69522	25	25				25			25				50%	50%	0%	0%
69548	20		20		20						20	20	40%	0%	40%	20%
69643	20		20		20					20		20	40%	20%	20%	20%
69725	25		25		25							25	50%	0%	25%	25%
69725	20				20	20		20				20	40%	20%	0%	40%
69738	20		20		20					20	20		40%	20%	40%	0%
69821	25		25		25						25		50%	0%	50%	0%
69821	20				20	20		20			20		40%	20%	20%	20%
69845	20		20		20				20			20	60%	0%	20%	20%
69916	25		25		25					25			50%	25%	25%	0%
69916	20				20	20		20		20			40%	40%	0%	20%
69940	20		20		20				20		20		60%	0%	40%	0%
70000			25		75								75%	0%	25%	0%
70000	33		33		33								67%	0%	33%	0%
70000	25				25	25		25					50%	25%	0%	25%

Table A.6: Combinations of generic requirements at MS numbers in the range 60001 to 80000 (details of headings given at end of table)

MS No.	n10010	n10007	n10005	n10001	n05010	n05007	n05005	n05001	n00110	n00107	n00105	n00101	% ps10	% ps7	% ps5	% ps 1
70036	20		20		20				20	20			60%	20%	20%	0%
70120	25		25		25				25				75%	0%	25%	0%
70120	20				20	20		20	20				60%	20%	0%	20%
70269	20	20			20		20					20	40%	20%	20%	20%
70349	20	20			20		20				20		40%	20%	40%	0%
70429	20	20			20		20			20			40%	40%	20%	0%
70500	25	25			25		25						50%	25%	25%	0%
70598	20	20			20		20		20				60%	20%	20%	0%
70750	30	30			20		15	5					50%	30%	15%	5%
71071	25	25			20		20						50%	28%	22%	0%
71764	20	35			25	10						10	45%	45%	0%	10%
71848	30				15			30	25				70%	0%	0%	30%
72100	25	25			25	10	15						50%	35%	15%	0%
73000	25	25			30		20						55%	25%	20%	0%
73472	20	15					5				5	55	20%	15%	10%	55%
73504	20	15					5				10	50	20%	15%	15%	50%
73768	20	20								20	20	20	20%	40%	20%	20%
73891	25	25									25	25	25%	25%	25%	25%
74010	25	25								25		25	25%	50%	0%	25%
74020	20						20			20	20	20	20%	20%	40%	20%
74020	20	20							20		20	20	40%	20%	20%	20%
74129	25	25								25	25		25%	50%	25%	0%
74134	33	33										33	33%	33%	0%	33%
74138	20	20							20	20		20	40%	40%	0%	20%
74184	25						25				25	25	25%	0%	50%	25%
74254	33	33									33		33%	33%	33%	0%
74256	20	20			20	20						20	40%	40%	0%	20%
74256	20	20							20	20	20		40%	40%	20%	0%
74262	25	25							25			25	50%	25%	0%	25%
74336	20	20			20	20					20		40%	40%	20%	0%
74342	25						25			25		25	25%	25%	25%	25%
74353	20						20		20		20	20	40%	0%	40%	20%
74373	33	33								33			33%	67%	0%	0%
74381	25	25							25		25		50%	25%	25%	0%
74415	20	20			20	20				20			40%	60%	0%	0%
74500	50	50											50%	50%	0%	0%
74500	25	25											50%	50%	0%	0%
74500	25	25											50%	50%	0%	0%
74500	25	25			25	25							50%	50%	0%	0%
74500	25	25							25	25			50%	50%	0%	0%
74500	25						25			25	25		25%	25%	50%	0%
74506	20				20	20	20					20	40%	20%	20%	20%
74510	20						20		20	20		20	40%	20%	20%	20%

Table A.6: Combinations of generic requirements at MS numbers in the range 60001 to 80000 (details of headings given at end of table)

MS No.	n10010	n10007	n10005	n10001	n05010	n05007	n05005	n05001	n00110	n00107	n00105	n00101	% ps10	% ps7	% ps5	% ps 1
74510	33						33					33	33%	0%	33%	33%
74585	20	20			20	20			20				60%	40%	0%	0%
74602	20				20	20	20				20		40%	20%	40%	0%
74627	33	33							33				67%	33%	0%	0%
74634	20				20			20			20	20	40%	0%	20%	40%
74667	20						20		20	20	20		40%	20%	40%	0%
74669	33						33				33		33%	0%	67%	0%
74678	25						25		25			25	50%	0%	25%	25%
74697	20				20	20	20			20			40%	40%	20%	0%
74752	20				20			20		20		20	40%	20%	0%	40%
74800	25				25	25	25						50%	25%	25%	0%
74828	33						33			33			33%	33%	33%	0%
74836	25						25		25		25		50%	0%	50%	0%
74871	20				20			20		20	20		40%	20%	20%	20%
74881	25				25			25				25	50%	0%	0%	50%
74900	20				20	20	20		20				60%	20%	20%	0%
74993	25						25		25	25			50%	25%	25%	0%
75000	50						50						50%	0%	50%	0%
75000	25						25						50%	0%	50%	0%
75000	25						25						50%	0%	50%	0%
75000	25				25			25			25		50%	0%	25%	25%
75005	20				20			20	20			20	60%	0%	0%	40%
75119	25				25			25		25			50%	25%	0%	25%
75124	20				20			20	20		20		60%	0%	20%	20%
75166	33						33		33				67%	0%	33%	0%
75243	20				20			20	20	20			60%	20%	0%	20%
75250	75			25									75%	0%	0%	25%
75250	33				33			33					67%	0%	0%	33%
75373	25				25			25	25				75%	0%	0%	25%
75912	45	35				10						10	45%	45%	0%	10%
76071	30				20			25				25	50%	0%	0%	50%
76185	30				20			25			25		50%	0%	25%	25%
77050	55	45											55%	45%	0%	0%
77154	35				15			25				25	50%	0%	0%	50%
77899	20	20			15						20	25	35%	20%	20%	25%
77979	15	20			25						20	20	40%	20%	20%	20%
78057	15	20			25				5		15	20	45%	20%	15%	20%
79071	20	20			20						20	20	40%	20%	20%	20%
79167	20	20			20					20		20	40%	40%	0%	20%
79262	20	20			20					20	20		40%	40%	20%	0%
79287	25	25			25							25	50%	25%	0%	25%
79369	20	20			20				20			20	60%	20%	0%	20%
79382	25	25			25						25		50%	25%	25%	0%

Table A.6: Combinations of generic requirements at MS numbers in the range 60001 to 80000 (details of headings given at end of table)

MS No.	n10010	n10007	n10005	n10001	n05010	n05007	n05005	n05001	n00110	n00107	n00105	n00101	% ps10	% ps7	% ps5	% ps 1
79464	20	20			20				20		20		60%	20%	20%	0%
79478	25	25			25					25			50%	50%	0%	0%
79560	20	20			20				20	20			60%	40%	0%	0%
79600		25			75								75%	25%	0%	0%
79600	33	33			33								67%	33%	0%	0%
79681	25	25			25				25				75%	25%	0%	0%
79950	20				20		15	5	40				80%	0%	15%	5%

Notes:

MS No. MS number
n10010 Number of generic requirements with a weighting of 100 and product score of 10
n10007 Number of generic requirements with a weighting of 100 and product score of 7
n10005 Number of generic requirements with a weighting of 100 and product score of 5
n10001 number of generic requirements with a weighting of 100 and product score of 1
n05010 number of generic requirements with a weighting of 50 and product score of 10
n05007 number of generic requirements with a weighting of 50 and product score of 7
n05005 number of generic requirements with a weighting of 50 and product score of 5
n05001 number of generic requirements with a weighting of 50 and product score of 1
n00110 number of generic requirements with a weighting of 1 and product score of 10
n00107 number of generic requirements with a weighting of 1 and product score of 7
n00105 number of generic requirements with a weighting of 1 and product score of 5
n00101 number of generic requirements with a weighting of 1 and product score of 1

%ps10 percentage of generic requirements with a product score of 10
%ps7 percentage of generic requirements with a product score of 7
%ps5 percentage of generic requirements with a product score of 5
%ps1 percentage of generic requirements with a product score of 1

Table A.7: Combinations of generic requirements at MS numbers in the range 80001 to 100000 (details of headings given at end of table)

MS No.	n10010	n10007	n10005	n10001	n05010	n05007	n05005	n05001	n00110	n00107	n00105	n00101	% ps10	% ps7	% ps5	% ps 1
80455	20				20		20					40	40%	0%	20%	40%
80574	20				20		20				20	20	40%	0%	40%	20%
80693	20				20		20			20		20	40%	20%	20%	20%
80812	20				20		20			20	20		40%	20%	40%	0%
80851	25				25		25					25	50%	0%	25%	25%
80946	20				20		20		20			20	60%	0%	20%	20%
80970	25				25		25				25		50%	0%	50%	0%
81064	20				20		20		20		20		60%	0%	40%	0%
81090	25				25		25			25			50%	25%	25%	0%
81183	20				20		20		20	20			60%	20%	20%	0%
81250	75		25										75%	0%	25%	0%

Table A.7: Combinations of generic requirements at MS numbers in the range 80001 to 100000 (details of headings given at end of table)

MS No.	n10010	n10007	n10005	n10001	n05010	n05007	n05005	n05001	n00110	n00107	n00105	n00101	% ps10	% ps7	% ps5	% ps 1
81250	33				33		33						67%	0%	33%	0%
81343	25				25		25		25				75%	0%	25%	0%
81863	20					20				20	20	20	20%	40%	20%	20%
81941	20					20				20	30	10	20%	40%	30%	10%
82079	25					25					25	25	25%	25%	25%	25%
82196	20					20			20		20	20	40%	20%	20%	20%
82237	25					25				25		25	25%	50%	0%	25%
82353	20					20			20	20		20	40%	40%	0%	20%
82395	25					25				25	25		25%	50%	25%	0%
82457	33					33						33	33%	33%	0%	33%
82510	20					20			20	20	20		40%	40%	20%	0%
82572	25					25			25			25	50%	25%	0%	25%
82616	33					33					33		33%	33%	33%	0%
82730	25					25			25		25		50%	25%	25%	0%
82775	33					33				33			33%	67%	0%	0%
82888	25					25			25	25			50%	50%	0%	0%
83000	50					50							50%	50%	0%	0%
83000	25					25							50%	50%	0%	0%
83000	25					25							50%	50%	0%	0%
83071	25	20			30				25				80%	20%	0%	0%
83113	33					33			33				67%	33%	0%	0%
84000	35				5	25	5		10			20	50%	25%	5%	20%
84094	35				5	25	5		15			15	55%	25%	5%	15%
85091	35				10	15	10					30	45%	15%	10%	30%
85857	75							25					75%	0%	0%	25%
85898	40				5	15	10		5		10	15	50%	15%	20%	15%
86485	20				20	20					15	25	40%	20%	15%	25%
86515	20				20	20					20	20	40%	20%	20%	20%
86634	20				20	20				20		20	40%	40%	0%	20%
86752	20				20	20				20	20		40%	40%	20%	0%
86821	25				25	25						25	50%	25%	0%	25%
86886	20				20	20			20			20	60%	20%	0%	20%
86940	25				25	25					25		50%	25%	25%	0%
87005	20				20	20			20		20		60%	20%	20%	0%
87060	25				25	25				25			50%	50%	0%	0%
87124	20				20	20			20	20			60%	40%	0%	0%
87250	75	25											75%	25%	0%	0%
87250	33				33	33							67%	33%	0%	0%
87313	25				25	25			25				75%	25%	0%	0%
87926	25				30	25			30				77%	23%	0%	0%
87990	25				20	20						35	45%	20%	0%	35%
88017	25				20	20					5	30	45%	20%	5%	30%
88963	25				25	20			5	5	20		55%	25%	20%	0%

Table A.7: Combinations of generic requirements at MS numbers in the range 80001 to 100000 (details of headings given at end of table)

MS No.	n10010	n10007	n10005	n10001	n05010	n05007	n05005	n05001	n00110	n00107	n00105	n00101	% ps10	% ps7	% ps5	% ps 1
89286	75						25						75%	0%	25%	0%
89569	30				30			10				30	60%	0%	0%	40%
89861	30				20	20			30				80%	20%	0%	0%
90050	30				25	20			10			15	65%	20%	0%	15%
90332	30				25	20			25				80%	20%	0%	0%
91030	30				15	15			15			25	60%	15%	0%	25%
91282	30				20	15						35	50%	15%	0%	35%
91948	30				25	15					30		55%	15%	30%	0%
92091	30				25	15				30			55%	45%	0%	0%
92714	75					25							75%	25%	0%	0%
93077	35				25	15			25				85%	15%	0%	0%
93417	30				25	5	5		35				90%	5%	5%	0%
93514	30				30	5	5		15	5	5	5	75%	10%	10%	5%
93986	35				25	5	5		25	5			85%	10%	5%	0%
94034	35				25	5	5		30				90%	5%	5%	0%
94972	40				35	5	5		15				90%	5%	5%	0%
95885	35				45			5	15				95%	0%	0%	5%
96049	40				40			5	15				95%	0%	0%	5%
97007	40				40		5		15				95%	0%	5%	0%
97117	25											75	25%	0%	0%	75%
97816	25										75		25%	0%	75%	0%
97816	25									25	25	25	25%	25%	25%	25%
97837	20								20	20	20	20	40%	20%	20%	20%
97917	80				15		5						95%	0%	5%	0%
97968	40				40	5			25				95%	5%	0%	0%
98026	90				5		5						95%	0%	5%	0%
98044	40				45	5			20				95%	5%	0%	0%
98294	33										33	33	33%	0%	33%	33%
98311	25								25		25	25	50%	0%	25%	25%
98515	25									75			25%	75%	0%	0%
98529	33									33		33	33%	33%	0%	33%
98529	20				20					20	20	20	40%	20%	20%	20%
98544	25								25	25		25	50%	25%	0%	25%
98692	95					5							95%	5%	0%	0%
98765	33									33	33		33%	33%	33%	0%
98777	25								25	25	25		50%	25%	25%	0%
98855	25				25						25	25	50%	0%	25%	25%
98863	20				20				20		20	20	60%	0%	20%	20%
99013	25				25					25		25	50%	25%	0%	25%
99020	20				20				20	20		20	60%	20%	0%	20%
99020	50											50	50%	0%	0%	50%
99020	25											25	50%	0%	0%	50%
99020	25											25	50%	0%	0%	50%

Table A.7: Combinations of generic requirements at MS numbers in the range 80001 to 100000 (details of headings given at end of table)

MS No.	n10010	n10007	n10005	n10001	n05010	n05007	n05005	n05001	n00110	n00107	n00105	n00101	% ps10	% ps7	% ps5	% ps 1
99029	33								33			33	67%	0%	0%	33%
99171	25				25					25	25		50%	25%	25%	0%
99176	20				20				20	20	20		60%	20%	20%	0%
99257	50										50		50%	0%	50%	0%
99257	25										25		50%	0%	50%	0%
99257	25										25		50%	0%	50%	0%
99265	33								33		33		67%	0%	33%	0%
99344	33				33							33	67%	0%	0%	33%
99349	25				25				25			25	75%	0%	0%	25%
99495	50									50			50%	50%	0%	0%
99495	25									25			50%	50%	0%	0%
99495	25									25			50%	50%	0%	0%
99500	33								33	33			67%	33%	0%	0%
99503	33				33						33		67%	0%	33%	0%
99507	25				25				25		25		75%	0%	25%	0%
99662	33				33					33			67%	33%	0%	0%
99664	25				25				25	25			75%	25%	0%	0%
99671	75											25	75%	0%	0%	25%
99751	75										25		75%	0%	25%	0%
99831	75									25			75%	25%	0%	0%
100000	100												100%	0%	0%	0%
100000	50				50								100%	0%	0%	0%
100000	50								50				100%	0%	0%	0%
100000	75				75								100%	0%	0%	0%
100000	75								75				100%	0%	0%	0%
100000	25				25								100%	0%	0%	0%
100000	25								25				100%	0%	0%	0%
100000	25				25								100%	0%	0%	0%
100000	25								25				100%	0%	0%	0%
100000	25				25								100%	0%	0%	0%
100000	25								25				100%	0%	0%	0%

Table A.7: Combinations of generic requirements at MS numbers in the range 80001 to 100000 (details of headings given at end of table)

MS No.	n10010	n10007	n10005	n10001	n05010	n05007	n05005	n05001	n00110	n00107	n00105	n00101	% ps10	% ps7	% ps5	% ps 1
100000	33				33				33				100%	0%	0%	0%

Notes:

MS No.	MS number
n10010	Number of generic requirements with a weighting of 100 and product score of 10
n10007	Number of generic requirements with a weighting of 100 and product score of 7
n10005	Number of generic requirements with a weighting of 100 and product score of 5
n10001	number of generic requirements with a weighting of 100 and product score of 1
n05010	number of generic requirements with a weighting of 50 and product score of 10
n05007	number of generic requirements with a weighting of 50 and product score of 7
n05005	number of generic requirements with a weighting of 50 and product score of 5
n05001	number of generic requirements with a weighting of 50 and product score of 1
n00110	number of generic requirements with a weighting of 1 and product score of 10
n00107	number of generic requirements with a weighting of 1 and product score of 7
n00105	number of generic requirements with a weighting of 1 and product score of 5
n00101	number of generic requirements with a weighting of 1 and product score of 1
%ps10	percentage of generic requirements with a product score of 10
%ps7	percentage of generic requirements with a product score of 7
%ps5	percentage of generic requirements with a product score of 5
%ps1	percentage of generic requirements with a product score of 1

Appendix B Evaluation of Construction Arisings

B.1 Production of Construction Arisings

Samples of the demolition arisings were obtained from the Ardler multi-storey site (Dundee, Scotland) were collected in bags, each bag containing approximately 30 kg of the samples. A production summary of demolition arisings is given in Table B.1. Samples were taken from all stockpiles on the demolition site based on guidelines given elsewhere (British Standards Institution 1989, Smith and Collis 1993). Grading and visual observation for samples of demolition arisings is shown as Table B.2.

The roadway arisings were obtained from Greendykes road, Dundee. The roadway structure was 100 mm of asphalt surfacing and 600 mm of stone setts, with concrete kerb along the sides. Hence, the material consisted of mainly crushed rock, concrete and bituminous mixes. The materials was produced in one pass through the jaw crusher with an opening of 75 mm. Due to the source of the material, it was relatively free of “contaminants”.

Table B.1: Production of Demolition Arisings

Sample code	Number of samples	Production process
75DP	20	Crushed demolition arising was produced in one pass through the jaw crusher with the discharge setting at 75 mm. Prior to crushing, finer material (less than 50 mm) was removed via the vibrating grizzly screen and re-introduced, upstream, onto the discharge conveyor with the crushed material.
50DP	20	Crushed demolition arising was produced in one pass through the jaw crusher with the discharge setting at 75 mm. Prior to crushing, finer material (less than 50 mm) was removed via the vibrating grizzly screen and re-introduced, upstream, onto the discharge conveyor with the crushed material. The material downstream of the discharge conveyor was subsequently passed through a single 50 mm screen.
75GP	20	crushed demolition arising was produced in one pass through the jaw crusher with the discharge setting at 75 mm. Prior to crushing, finer material (less than 50 mm) was removed via the vibrating grizzly chute and discharged via the discharge dirt conveyor (i.e. the finer material was not re-introduced into the process).

Table B.2: Grading and Visual Observation for Samples of Demolition Arisings

Material Code	Grading: Cumulative percent passing sieve size (mm)							Description (based on grading and on at least two independent visual observations)
	75	37.5	20	10	5	0.6	0.075	
50DPA1	100	99	89	64	39	14	1	Visual brick:concrete = 25:75 after air drying (based on coarse aggregate fraction). Material appeared not as "peaty" in colour when wet as did 75DPA1 and 75DPA2. Material changed from dark grey (when wet) to light grey (when dry). Gap-graded; slight 'visual' 'noticeable' observation at coarse aggregate end. Looked reasonable as a construction material (sub-base?). Greatest proportion of contaminants retained on 5 mm sieve.
50DPA2	100	98	91	69	44	15	1	Visual brick:concrete = almost 100% concrete (at least 90%) - based on coarse aggregate fraction. Material appeared "peaty" in colour when wet. Material changed from dark grey (when wet) to light grey (when dry). Proportion of contaminants similar to that of 75GPA1 and 75GPA2. Very small proportion of large chunks (>75 mm) when compared to 75GPA1 and 75GPA2. May contain larger proportion of fines when compared to 50DPA1, 75DPA1 and 75DPA2. May contain less brick content when compared to 50DPA1, 75DPA1 and 75DPA2. May be more brick in 50DPA2 when compared to 75GPA1 and 75GPA2. Greatest proportion of contaminants retained on 5 mm sieve.
50DPB1	100	85	77	60	43	15	1	Visual brick:concrete = 10:90 after air drying, (based on coarse aggregate fraction). Large chunks of predominantly concrete (probably < 75 mm). Visual appearance indicates relatively small proportion of contaminants. Half dry - appeared peaty (due to dampness). Grading looks "fine" relative to type 2 grading. Contained peculiar metal (part of lead pipe?). Several (8) large lumps with (maybe) a gap to the next size down. Fine material appear similar to that of 50DPC1 and 50DPC2. Low proportion of brick and no large brick pieces. Less contaminants than in 50DPC1 and 50DPC2. Greatest proportion of contaminants retained on 5 mm sieve.
50DPB2	100	92	75	52	33	12	1	Predominantly concrete, based on coarse aggregate fraction. A few large aggregates (greater than 37.5 mm). Relatively low proportion of contaminants. Relatively low proportion of brick material. Greatest proportion of contaminants retained on 5 mm sieve. Grading curve lies approximately in the middle of the sub-base Type 1 envelope and along the lower (coarse) limit of the 50DP envelope.
50DPC1	100	98	89	69	47	18	1	Visual brick:concrete = 10:90 after air drying (based on coarse aggregate fraction). Similar state of affairs as with 50DPB1 except that not as many large chunks of crushed material. Contains dark "soil" material. Absence of large material, similar (usual) amounts of contaminants to 50DPC2, but more than 50DPB1. low proportion of brick and no large pieces. Fine material similar to that of 50DPB1 and 50DPC2. Greatest proportion of contaminants in mass retained on 5 mm sieve. Three chunks of concrete and one chunk of brick retained on 37.5 mm sieve.

Table B.2: Grading and Visual Observation for Samples of Demolition Arisings

Material Code	Grading: Cumulative percent passing sieve size (mm) 75	37.5	20	10	5	0.6	0.075	Description (based on grading and on at least two independent visual observations)
50DPC2	100	99	92	75	52	19	1	Visual brick:concrete = 10:90, after air drying (based on coarse aggregate fraction). Agglomeration of particles up to 50 mm size (may be soil material in large amounts). Appears well graded. Maximum aggregate size < 50 mm, i.e. large chunks not seen. Similar proportion of contaminants to 50DPC1. Absence of large material, similar (usual) amounts of contaminants to 50DPC2, but more than 50DPB1. Low proportion of brick and no large pieces. Fine material similar to that of 50DPB1 and 50DPC2. Greatest proportion of contaminants in mass retained on 5 mm sieve. Most of the "soil" material retained on 10 mm (possibly broken down through crushing while sieving). Mass retained on 37.5 mm = four chunks of concrete only.
50DPD1	100	99	93	67	36	12	1	Visual brick:concrete = 10:90 after air drying (based on coarse aggregate fraction). Not one single large chunk present. Likely to be on the finer side of type 1 sub-base. Looks well-graded. Relatively low proportion of waste (especially when compared to 75GPC1). half dry if not three-quarters dry. Very similar to 50DPD2. Lacking in any large particles. has small amount of contaminants. Devoid of any pieces of brick > 25 mm. Appears to have quite a bit of dust but this may be an impression created by the relatively large amount of generally fine material. Greatest proportion of contaminants in mass retained on 5 mm sieve. Two pieces of concrete (approx. 50 mm size) retained on 37.5 mm sieve.
50DPD2	100	99	92	66	45	13	1	Visual brick:concrete = 10:90 after air drying (based on coarse aggregate fraction). Not one single large chunk present. Likely to be on the finer side of type 1 sub-base. Looks well-graded. Relatively low proportion of waste (especially when compared to 75GPC1). Half dry if not three-quarters dry. Very similar to 50DPD1. Lacking in any large particles. Has small amount of contaminants. Devoid of any pieces of brick > 25 mm. Appears to have quite a bit of dust but this may be an impression created by the relatively large amount of generally fine material. Greatest proportion of contaminants in mass retained on 5 mm sieve. Three chunks of concrete retained on 37.5 mm.
50DPE1	100	100	91	57	33	11	1	Visual brick:concrete = 35:65 on day of air drying (based on coarse aggregate fraction). High relative proportion of bricks in coarse aggregate fractions. Appears well-graded. Half dry on day of air drying. High proportion of fines, with grading probably towards finer end of type 1 sub-base. Appears well-graded with no very large pieces. Much higher proportion of bricks than 50DPE2. Moderate contaminants. Greatest proportion of contaminants in mass retained on 5 mm sieve. One chunk of concrete retained on 37.5 mm.

Table B.2: Grading and Visual Observation for Samples of Demolition Arisings

Material Code	Grading							Description (based on grading and on at least two independent visual observations)
	Cumulative percent passing sieve size (mm)							
	75	**37.5**	**20**	**10**	**5**	**0.6**	**0.075**	
50DPE2	100	100	93	75	51	20	1	Visual brick:concrete = 15:85 (based on coarse aggregate fraction). Half dry on day of air drying. No large chunks. Appears to have less brick chunks than 50DPE1. Appears well-graded (grading possibly well within type 1). Relatively low proportion of contaminants. Also low proportion, possibly retained on 37.5 mm sieve. Very low proportion of larger pieces. Apparently very high proportion fine material (appears rather "dusty"). Low proportion of brick. Small amount of contaminants. Greatest proportion of contaminants in mass retained on 5 mm sieve. One chunk of concrete retained on 37.5 mm sieve.
50DPF1	100	99	83	58	36	10	0	Visual brick:concrete = 15:85 on day of air drying (based on coarse aggregate fraction). Low proportion of contaminants (relatively speaking). Normal concrete/greyish colour. large chunks absent (appears few pieces to be retained on 37.5 mm). Sporadic brick fractions in > 20 mm <37.5 mm) size. May be at the upper end for type 1 (looks quite fine). Damp (three-quarters dry) on day of drying. No large pieces. Appears well graded. Small proportion of brick pieces and all these of small size. Low proportion of contaminants. Sample is "concrete colour". Greatest proportion of contaminants in mass retained on 5 mm sieve. Three chunks of concrete retained on 37.5 mm sieve (high proportion of clinker (approx. 40%) retained on 20 and 10 mm sieves).
50DPF2	100	97	85	64	46	15	1	Visual brick:concrete = 15:85 on day of air drying (based on coarse aggregate fraction). Medium range proportion of contaminants (relatively speaking). Normal concrete/greyish colour. Large chunks absent (appears few pieces to be retained on 37.5 mm). Sporadic brick fractions in > 20 mm (<37.5 mm) size. May be at the upper end for type 1 (looks quite fine). Damp (three-quarters dry) on day of drying. No large pieces. Appears well graded. Small proportion of brick pieces and all these of small size. Low proportion of contaminants. Sample is "concrete colour". Greatest proportion of contaminants in mass retained on 5 mm sieve. Six chunks of material (1 chunk = clinker) retained on 37.5 mm sieve. High proportion of clinker retained on 20 and 10 mm sieves.
50DPG1	100	100	92	76	56	19	1	Visual brick:concrete = 10:90 (based on coarse aggregate fraction). Appears to have an extra high proportion of fines. Usual greyish concrete colour. No large chunks and if any retained on 37.5 mm possibly not more than 4 pieces. Partly damp. Low proportion of brick. Very few large pieces of material. Lots of fines. Low quantity of contaminants compared to 50DPG2. Greatest proportion of contaminants in mass retained on 5 mm sieve.

Table B.2: Grading and Visual Observation for Samples of Demolition Arisings

Material Code	Grading: Cumulative percent passing sieve size (mm)							Description (based on grading and on at least two independent visual observations)
	75	37.5	20	10	5	0.6	0.075	
50DPG2	100	99	92	79	57	19	1	Visual brick:concrete = 10:90 (based on coarse aggregate fraction). Appears to have an extra high proportion of fines. Usual greyish concrete colour. No large chunks and if any retained on 37.5 mm possibly not more than 4 pieces. Partly damp. Low proportion of brick. Very few large pieces of material. Lots of fines. Moderate quantity of contaminants compared to 50DPG1. Greatest proportion of contaminants in mass retained on 5 mm sieve. Two pieces of concrete lumps retained on 37.5 mm (only slightly greater than 37.5 mm).
50DPH1	100	99	89	63	41	13	1	Visual brick:concrete = 15:85 (based on coarse aggregate fraction). Normal greyish concrete colour. No very large chunks present. Very large amount of fines. Some brick > 20 mm. Contaminants predominantly timber. Dry on day of air drying. Relatively small amounts of brick content with 50DPH1 > 50DPH2. Has quite a high amount of small fractions. Moderate amount of contaminants. Greatest proportion of contaminants in mass retained on 5 mm sieve. Four pieces (slightly > 37.5 mm) retained on 37.5 mm sieve (1 brick, 1 concrete).
50DPH2	100	99	94	72	46	14	1	Visual brick:concrete = 15:85 (based on coarse aggregate fraction). Normal greyish concrete colour. No very large chunks present. Very large amount of fines. Some brick > 20 mm. Contaminants predominantly timber (proportion of contaminants very small). Dry on day of air drying. Relatively small amounts of brick content with 50DPH1 > 50DPH2. Has quite a high amount of small fractions. Has very small amount of contaminants. Greatest proportion of contaminants in mass retained on 5 mm sieve. Three pieces (slighlty > 37.5 mm) retained on 37.5 mm sieve.
50DPJ1	100	95	84	60	37	13	1	Visual brick:concrete = 10:90 (based on coarse aggregate fraction). Dry on day of air drying. Colour lighter than 75DPH2. One or two (probably at the most) of chunks retained on 37.5 mm (and 75 mm?). Looks well-graded and may fit within type 1. Predominantly concrete (very few, maybe 1/2 pieces, of bricks breeze present). Usual contaminants. Good grading of material and the customary amount of contaminants. Appears to have a low brick content (has a few "oversize" pieces). Greatest proportion of contaminants in mass retained on 5 mm sieve.
50DPJ2	100	97	86	62	37	14	1	Visual brick:concrete = 10:90 (based on coarse aggregate fraction). Dry on day of air drying. Colour lighter than 75DPH2. One or two (probably at the most) of chunks retained on 37.5 mm (and 75 mm?). Looks well-graded and may fit within type 1. Predominantly concrete (very few, maybe 1/2 pieces, of bricks breeze present). Usual contaminants. Good grading of material and the customary amount of contaminants. Appears to have a low brick content. Greatest proportion of contaminants in mass retained on 5 mm sieve. Three 3 concrete pieces retained on 37.5 mm sieve.

Table B.2: Grading and Visual Observation for Samples of Demolition Arisings

Material Code	Grading							Description (based on grading and on at least two independent visual observations)
	Cumulative percent passing sieve size (mm)							
	75	37.5	20	10	5	0.6	0.075	
50DPK1	100	99	92	77	56	20	1	Predominantly concrete (grey “concrete” colour). Relatively high percent of fines (appears rather dusty). Small amount of contaminants (mostly timber). A few large aggregates in the 50 - 75 mm range. Appears to have very low brick. Greatest proportion of contaminants retained on 5 mm sieve. Three concrete aggregates (slightly greater than 37.5 mm) were retained on the 37.5 mm sieve. Grading curve (5 – 10 mm) lies partially above the sub-base Type 1 envelope and along the upper (fine) limit of the 50DP envelope
50DPK2	100	100	91	73	50	16	1	Visual brick:concrete = 10:90 before air drying (based on coarse aggregate fraction). Normal grey concrete colour. No large chunks present. A high percent of fines (if any retained on 37.5 mm sieve not more than 2 chunks). May be close to upper boundary of type 1 sub-base. Usual contaminants (mostly timber). No large pieces. Moderate amount of contaminants. No pieces in 50 - 75 mm range. Appears to have very low brick content, and high proportion of fine material. Appears rather "dusty". Greatest proportion of contaminants in mass retained on 5 mm sieve. Two pieces (slighty > 37.5 mm) retained on 37.5 mm sieve (1 breeze, 1 dark brick).
75DPA1	100	77	65	49	32	12	1	Visual brick:concrete = 40:60 before drying, "changed" to possibly 25:75 after drying (based on coarse aggregate fraction). Material appeared "peaty" in colour when wet but as it dried out it showed a greyish (concrete) colour. Appeared to have less brick (than 75DPA2) but difficult to tell. More big bricks (chunks (i.e. quarter bricks of irregular shape) in the mixture). Gap graded of 'visual' 'noticeable' difference. Plenty of fines. Looked reasonable as a construction material (sub-base?). Greatest proportion of contaminants retained on 5 mm sieve.
75DPA2	100	84	67	46	29	12	2	Visual brick:concrete = 60:40 before drying, "changed" to possibly 15:85 after drying. (based on coarse aggregate fraction). Material appeared "peaty" in colour when wet but as it dried out it showed a greyish (concrete) colour. Plenty of fines. Greatest proportion of contaminants in mass retained on 5 mm sieve. High proportion of burnt clay bricks retained on 20 mm and 10 mm sieves.
75DPB1	100	75	57	40	25	9	0	High proportion of concrete, based on coarse aggregate fraction. High proportion of coarse aggregates (greater than 37.5 mm) – some large brick aggregates. Low proportion of fines. Greatest proportion of contaminants retained on 5 mm sieve. Grading curve lies approximately along the lower limit of the sub-base Type 1 envelope and along the lower (coarse) limit of the 75DP envelope

Table B.2: Grading and Visual Observation for Samples of Demolition Arisings

Material Code	Grading: Cumulative percent passing sieve size (mm)							Description (based on grading and on at least two independent visual observations)
	75	37.5	20	10	5	0.6	0.075	
75DPB2	100	89	77	58	37	12	1	Visual brick:concrete = greater proportion of concrete 10:90, after air drying (based on coarse aggregate fraction). Material appeared "peaty" in colour when wet (i.e. on day of drying). Self cementing evident (20 mm and larger agglomerated particles easily crumbled in hands). Left in "50 kg nominal" bags (under loose compaction somewhat) without sealing for approx. 3 weeks. Is peatiness/self cementation a function of time left in bag or a function of the constituents - including amount of moisture? Large chunks (>75 mm) of material (predominantly concrete) - not as many as in 75GPB1. Less large brick chunks than in 75GPB2 and 75GPB1. Very little brick. Appears good grading spread. Same proportion of contaminants as 75GPB1 and 75GPB2. Roughly same proportion of large chunks as 75GPB1 and 75GPB2. Greatest proportion of contaminants in mass retained on 5 mm sieve. Contained fibre wood insulation. Agglomerated particles broken down during sieving.
75DPC1	100	83	61	43	29	13	1	Visual brick:concrete = more likely 40:60 (based on coarse aggregate fraction). Appears to have a uniform mixture of breeze blocks, concrete and bricks in coarse and finer (down to 5 mm) aggregate fractions. Relatively large proportion of contaminants. Material appeared quite dirty/sandy/dusty on date of air drying. Contained large chunks of which the maximum size was greater than that of 75DPC2. Final colour after air drying darker than previous samples already sieved (brownish colour) - contribution - soil, brick, ...? INTERESTING TO SEE SUBSEQUENT RESULTS. Lots of large fragments and a lot of medium sized pieces. Much larger proportion of bricks than recent samples. Higher proportion of concrete. certainly bigger "items" of waste. Greatest proportion of contaminants in mass retained on 5 mm sieve. Approx. 10 - 20% by volume of burnt bricks on masses retained on 5 and 10 mm sieves (i.e. without clayey brick part).

Table B.2: Grading and Visual Observation for Samples of Demolition Arisings

Material Code	Grading							Description (based on grading and on at least two independent visual observations)
	Cumulative percent passing sieve size (mm)							
	75	37.5	20	10	5	0.6	0.075	
75DPC2	100	84	65	46	32	14	1	Visual brick:concrete = more likely 40:60 (based on coarse aggregate fraction). Appears to have a uniform mixture of breeze blocks, concrete and bricks in coarse and finer (down to 5 mm) aggregate fractions. Relatively small proportion of contaminants (compared to 75DPC1). Material appeared quite dirty/sandy/dusty on date of air drying. Contained large chunks of which the maximum size was less than that of 75DPC1. Contained roof tiles, slate, ceramic wall tiles, and some flaky particles. Final colour after air drying darker than previous samples already sieved. Brownish colour and noticeably darker than 75DPC1 - contribution from brick, soil, ...? INTERESTING TO SEE SUBSEQUENT RESULTS Lower proportion of large pieces compared to 75DPC1. Proportion of brick may be similar to 75DPC1. Much less waste. Greatest proportion of contaminants in mass retained on 5 mm sieve. Approx. 10 - 20% by volume of burnt bricks on masses retained on 5 and 10 mm sieves (i.e. without clayey brick part).
75DPD1	100	88	73	53	34	11	0	Visual brick:concrete = 20:80 (based on coarse aggregate fraction) Large chunks (> 75 mm) - predominantly concrete (coarse aggregate also predominantly concrete). Quantity of contaminants in mid-range (contained rusty nails). Virtually dry on day of air drying with usual greyish concrete colour. Sporadic appearance of clay bricks and breeze blocks (> 5 mm). Appears well-graded. Similar to 75DPD2 with less overall larger pieces but a few very large pieces. Proportion of contaminants and bricks as per 75DPD2. Greatest proportion of contaminants in mass retained on 5 mm sieve.
75DPD2	100	76	61	43	27	10	0	Visual brick:concrete = 20:80 (based on coarse aggregate fraction). Large chunks (> 75 mm) - predominantly concrete (coarse aggregate also predominantly concrete). Quantity of contaminants in mid-range (contained rusty angle bead). Virtually dry on day of air drying with usual greyish concrete colour. Sporadic appearance of clay bricks and breeze blocks (> 5 mm). Appears well-graded. Appears to be a good mixture of all sizes with perhaps an "excess" of larger pieces. Small amounts of contaminants and relatively low proportion of brick. No large pieces of brick. Greatest proportion of contaminants in mass retained on 5 mm sieve.

Table B.2: Grading and Visual Observation for Samples of Demolition Arisings

Material Code	Grading							Description (based on grading and on at least two independent visual observations)
	Cumulative percent passing sieve size (mm)							
	75	**37.5**	**20**	**10**	**5**	**0.6**	**0.075**	
75DPE1	100	91	78	63	46	19	2	Visual brick:concrete = 65:35 (based on coarse aggregate fraction). Contains a high proportion of bricks (based on coarse aggregate fractions - colour was brick-like on day of air drying, may be due to brick content. Relatively low proportion of contaminants. More proportion of bricks in large chunks. May be gap-graded in 10/5 mm down to 0.6 mm. Has a much larger amount of brick pieces - very high compared to most samples seen so far. Also, has a distinct colour - could this be due to a large amount of brick? Lower proportion of large chunks compared to 75GPE1 and 75GPE2. Relatively low proportion of contaminants compared with samples previously seen. Greatest proportion of contaminants in mass retained on 5 mm sieve. Majority of mass retained on 37.5 mm are bricks (mass = 1389 kg).
75DPE2	100	94	83	66	46	18	2	Visual brick:concrete = 60:40 (based on coarse aggregate fraction). Contains a high proportion of bricks (based on coarse aggregate fractions - colour bricky on day of air drying, may be due to brick content. Relatively low proportion of contaminants. More proportion of bricks in large chunks. Has a much larger amount of brick pieces - very high compared to most samples seen so far. Also, has a distinct colour - could this be due to a large amount of brick? Lower proportion of large chunks compared to 75GPE1 and 75GPE2. Relatively low proportion of contaminants compared with samples previously seen. Greatest proportion of contaminants in mass retained on 5 mm sieve. 80 g of porous chalky chunk retained on 37.5 mm sieve. Large black brick chunks easily broken down. Some porous chunky material retained on 10 mm sieve.
75DPF1	100	90	76	57	38	12	1	Visual brick:concrete = 30:70 on day of air drying (based on coarse aggregate fraction). Dark in colour (proportion of brick/soil?). Large chunks of concrete > 75 mm. Almost dry. Some clear clay bricks of size > 37.5 mm plus some burnt clay bricks. Grading appears to be tending towards finer limit of 75DP samples. Usual constituents in contaminants. Has a few large lumps. An "earthy" colour. Relatively high proportion of brick and also of black bits (breeze block or burnt brick?). Dusty appearance. Moderate proportion of contaminants. Greatest proportion of contaminants in mass retained on 5 mm sieve.

Table B.2: Grading and Visual Observation for Samples of Demolition Arisings

Material Code	Grading							Description (based on grading and on at least two independent visual observations)
	Cumulative percent passing sieve size (mm)							
	75	37.5	20	10	5	0.6	0.075	
75DPF2 (outlier)	100	94	84	72	59	34	6	Visual brick:concrete = 30:70 on day of air drying (based on coarse aggregate fraction). Dark in colour (proportion of brick/soil?). Large chunks of concrete > 75 mm. Almost dry. One clear clay brick of size > 20 mm plus large chunks of clay bricks. Grading appears to be tending towards finer limit of 75DP samples. Peculiar constituents in contaminants (large wood splinters, wall paper audio tape strip, electric light fitting cable/housing - as if from another building). Overall appearance similar to 75DPF1. Has a few large lumps. An "earthy" colour. Relatively high proportion of brick and also of black bits (breeze block or burnt brick?). Dusty appearance. Moderate proportion of contaminants. Greatest proportion of contaminants in mass retained on 5 mm sieve. A high percentage of burnt clay bricks retained on 37.5, 20 and 10 mm sieves. On 37.5 mm sieve - 4 brick pieces, 1 breeze out of 12 pieces. Mass retained on 20 mm sieve an even mixture of concrete and bricks (clay/burnt), and clinker (same goes for mass retained on 10 mm).
75DPG1	100	90	80	61	42	17	2	Visual brick:concrete = 25:75 before air drying (based on coarse aggregate fraction). Appears dry on day of drying with a darkish colour (may be due to dark bricks). Large chunks of concrete material. Not as dark as 75DPF1/75DPF2. Appears well-graded with plenty of fines (may lie close to upper boundary of type 1). Usual contaminants (including wired glass, large timber pieces/splints). More coarse brick proportions than most other samples sieved so far. Seems to have higher proportion of larger particles than 75GPG1/75GPG2 and also a larger proportion at the "small end". Brick proportions appears slightly less than 75GPG1/75GPG2. Contaminants proportion similar to 75DPG2/75GPG1/75GPG2 and about the same and consistent with previous samples. Greatest proportion of contaminants in mass retained on 5 mm sieve. High percent (relatively) of breeze blocks retained on 20 mm sieve.
75DPG2	100	84	73	53	34	12	1	Visual brick:concrete = 25:75 before air drying (based on coarse aggregate fraction). Appears dry on day of drying with a darkish colour (maybe due to dark bricks). Large chunks of concrete material. Not as dark as 75DPF1/75DPF2. Appears well-graded with plenty of fines (may lie close to upper boundary of type 1). Fines may be less than in 75DPG1. Usual contaminants (including wired glass, large timber pieces/splints, fibre wool underlay). More coarse brick proportions than most other samples sieved so far. Tiles also present. Lighter in colour than 75DPG1. Seems to have higher proportion of larger particles than 75GPG1/75GPG2 and also a larger proportion at the "small end". Brick proportions appear slightly less than 75GPG1/75GPG2. Contaminants proportion similar to 75DPG1/75GPG1/75GPG2 and about the same and consistent with previous samples. Greatest proportion of contaminants in mass retained on 5 mm sieve.

Table B.2: Grading and Visual Observation for Samples of Demolition Arisings

Material Code	Grading: Cumulative percent passing sieve size (mm)							Description (based on grading and on at least two independent visual observations)
	75	37.5	20	10	5	0.6	0.075	
75DPH1	100	84	70	49	31	11	1	Visual brick:concrete = 15:85 (based on coarse aggregate fraction). Normal grey concrete colour. Quite a few large pieces of predominantly concrete (some breeze blocks included) - especially when compared to 50DPH1 and 50DPH2. Appears to have large proportion of fines compared to 75GPG2. Usual contaminants. Dry on day of air drying. Moderate amount of contaminants. Large proportion of brick (compared to 50DPH1/50DPH2) and having a few larger pieces. High amount of small fractions. Perhaps more evenly graded at the higher size end than some other "75" samples. Greatest proportion of contaminants in mass retained on 5 mm sieve.
75DPH2	100	86	66	45	28	9	0	Visual brick:concrete = 15:85 (based on coarse aggregate fraction). Normal grey concrete colour. Quite a few large pieces of predominantly concrete - especially when compared to 50DPH1 and 50DPH2. Appears to have large proportion of fines compared to 75GPG2. Usual contaminants. Dry on day of air drying. Few breeze blocks > 20 mm. Moderate amount of contaminants. Large proportion of brick (compared to 50DPH1/50DPH2) and having a few larger pieces. High amount of small fractions. Perhaps more evenly graded at the higher size end than some other "75" samples.
75DPJ1	100	97	89	69	46	15	1	Predominantly concrete (grey “concrete” colour). Some brick coarse aggregate fractions. Moderate amount of contaminants. Very few coarse aggregate fractions and a lot of fine material. Greatest proportion of contaminants retained on 5 mm sieve. Grading curve (fine aggregate part) lies partially in the middle and the remainder (coarse aggregate fraction) towards the upper limit of the sub-base Type 1 envelope. The grading curve lies along the upper (fine) limit of the 75DP envelope.
75DPJ2	100	83	64	43	27	9	1	Visual brick:concrete = 25:75 before air drying (based on coarse aggregate fraction). Slightly dark (due to dark bricks?) but not as “plasterboard” colour as 75DPJ1. High proportion of large chunks (some dark bricks present in sizes 37.5 mm to 20 mm). Similar proportion of fines and grading to 75DPJ1. Contaminants = metal wires, fibrewool underlay, (not much timber). Moderate amount of contaminants. low proportion of brick and appears to have a good range of grading. Quite a number of large pieces. Greatest proportion of contaminants in mass retained on 5 mm sieve.

Table B.2: Grading and Visual Observation for Samples of Demolition Arisings

Material Code	Grading: Cumulative percent passing sieve size (mm)							Description (based on grading and on at least two independent visual observations)
	75	37.5	20	10	5	0.6	0.075	
75DPK1	100	87	71	50	33	14	1	Visual brick:concrete = 30:70 before air drying (based on coarse aggregate fraction). Difficult to tell because of colour. Appears very dark (brown (or soily) in colour. Could be due to combination of dark bricks, red bricks (any soil?). Large chunks present (includes some red bricks). Dry on day of air drying. May be gap-graded (with high fines percent). Relatively low proportion of contaminants (usual contaminants). Appears well-graded with significant amount of large "lumps". Has distinctive colour presumably indicating presence of significant brick dust. Has higher visible brick content than 75GPK1/75GPK2. Lower contaminants than 75GPK1/75GPK2. Greatest proportion of contaminants in mass retained on 5 mm sieve.
75DPK2	100	92	79	59	40	16	2	Visual brick:concrete = 30:70 before air drying (based on coarse aggregate fraction). Difficult to tell because of colour. Appears dark but not as dark as 75DPK1 (i.e. nearing colour of samples with black/dark bricks). Could be due to combination of dark bricks, red bricks (any soil?). Large chunks present (includes some red bricks). Dry on day of air drying. May be gap-graded (with high fines percent). Relatively low proportion of contaminants (usual contaminants). Has lower contaminants than 75GPK1/75GPK2. Has higher visible brick content than 75GPK1/75GPK2. Has reasonable amount of large pieces. Greatest proportion of contaminants in mass retained on 5 mm sieve.
75GPA1	100	82	68	54	37	13	1	Visual brick:concrete = almost 100% concrete, at least 90% (based on coarse aggregate fraction). Material appeared not as "peaty" in colour when wet as did 75DPA1 and 75DPA2. Material changed from dark grey (when wet) to light grey (when dry). Proportion of contaminants similar to that of 50DPA2 and 75GPA2. Larger proportion of large chunks (>75 mm) when compared to 50DPA2. May contain larger proportion of fines when compared to 50DPA1, 75DPA1 and 75DPA2. May contain less brick content when compared to 50DPA1, 75DPA1 and 75DPA2 (may be less brick when compared to 50DPA2). Greatest proportion of contaminants in mass retained on 5 mm sieve. Quite a few contaminants retained on 0.6 mm sieve (i.e. compared to other samples).
75GPA2	100	75	58	44	30	10	1	Predominantly concrete (based on coarse aggregate fraction). High proportion of coarse aggregate particles (greater than 37.5 mm). Greatest proportion of contaminants retained on 5 mm sieve. High proportion of contaminants also retained on the 0.6 mm sieve. grading curve lies approximately along the lower limit of the sub-base Type 1 envelope and along the lower (coarse) limit of the 75GP envelope.

Table B.2: Grading and Visual Observation for Samples of Demolition Arisings

Material Code	Grading: Cumulative percent passing sieve size (mm)							Description (based on grading and on at least two independent visual observations)
	75	37.5	20	10	5	0.6	0.075	
75GPB1	100	80	69	51	34	12	1	Visual brick:concrete = greater proportion of concrete 15:85 after air drying (based on coarse aggregate fraction). Light grey (cementitious) on day of drying. Large chunks (>75 mm) of material (predominantly concrete, more chunks of bricks than 75DPB2). Large chunks of metal (peculiar). Self cementing evident (20 mm agglomerated particles easily crumbled in hands). Left in "50 kg nominal" bags without sealing for approx. 3 weeks. Material changed from dark grey (when wet) to light grey (when dry). Same proportion of contaminants as 75DPB2 and 75GPB2. Roughly same proportion of large chunks as 75DPB2 and 75GPB2. A few large bits of brick. Large bits of brick are bigger than in 75DPB2 and 75GPB2. Greatest proportion of contaminants in mass retained on 5 mm sieve. Some material > 37.5 mm noticed in breeze blocks. Aerated block pieces with rendering had steel wire protruding from rendering (> 37.5 mm).
75GPB2	100	84	74	54	36	12	1	Visual brick:concrete = greater proportion of concrete 15:85 after air drying, (based on coarse aggregate fraction). Light grey (cementitious) on day of drying. Large chunks (>75 mm) of material (predominantly concrete) but less than in 75GPB1 (more chunks of bricks than 75DPB2 - also included a large chunk of breeze block). More "peaty" in appearance than 75GPB1. Material changed from dark grey (when wet) to light grey (when dry). More bricks than in 75DPB2 and 75GPB1 (in mid-size range). Same proportion of contaminants as 75GPB1 and 75DPB2. Roughly same proportion of large chunks as 75GPB1 and 75DPB2. Greatest proportion of contaminants retained on 5 mm sieve.
75GPC1	100	91	73	41	22	7	1	Visual brick:concrete = 10:90 on day of air drying (based on coarse aggregate fraction). Appeared almost dry on day of air drying. Normal range (i.e. sizes) of large chunks. Contains plenty of timber splinters - makes up majority of contaminants. Appears quite dusty (probably fines content). Concrete predominant in coarse fractions. Low proportion of large material. Low proportion of brick. Certainly bigger "items" of contaminants. Greatest proportion of contaminants in mass retained on 5 mm sieve. A lot of contaminants removed during sieving (possibly 1-2% of previous volume). Most removed from masses retained on 5 mm and 10 mm sieves.

Table B.2: Grading and Visual Observation for Samples of Demolition Arisings

Material Code	Grading Cumulative percent passing sieve size (mm)							Description (based on grading and on at least two independent visual observations)
	75	37.5	20	10	5	0.6	0.075	
75GPC2	100	93	80	52	30	9	1	Visual brick:concrete = 10:90 (based on coarse aggregate fraction). One "extra large" chunk of concrete. concrete predominant in coarse aggregate fraction. Contaminants edging towards higher range. Material half dry on day of air drying. Looks well suited for type 1 grading. Plenty of "old fashioned" carpet underlay (i.e. wood fibre insulation). Extra underlay extracted just before sieving hence may extend volume of contaminants to at least 3%. A few large pieces though possibly a gap to the next sizes. Low proportion of brick and certainly bigger items of contaminants. Greatest proportion of contaminants in mass retained on 5 mm sieve. Thirteen pieces retained on 37.5 mm (approx. 50 mm size). A lot of carpet underlay retained on 5 mm.
75GPD1	100	81	69	50	32	10	0	Appeared virtually dry. Small proportion of contaminants. May be slightly gap-graded from large chunks to mass retained on 20 mm sieve. Two pieces of large brick chunks possibly retained on 75 mm (definitely on 37.5 mm); rest of the large chunks are concrete. Has a more "brick" appearance than other samples but not as much as 75DPC1/C2 samples (20% of that brick appearance). "Well-gradedness" may not be as superior as 50DPD2. Moderate amounts of contaminants. A few large pieces. Appears to be well-graded. Moderate proportion of brick pieces (or large pieces of brick). Larger proportion of brick than 50DPD1/D2. Greatest proportion of contaminants in mass retained on 5 mm sieve
75GPD2	100	89	72	51	31	11	1	Some large chunks of concrete (probably 1 or 2 > 75 mm). "semi-large" chunks - mixture of brick, block, concrete. May fit type 1 (i.e. excluding > 75 mm). Bigger size of individual contaminants consisting of mainly timber chips. Proportion of contaminants by volume probably in the mid-range. Colour similar to 75GPD1 (i.e. brick-like). Material dry. Appears to have quite a bit of dust but this may be an impression created by the relatively large amount of generally fine material. Small amount of contaminants. Quite a bit of big stuff, including some brick, but overall a small percentage of brick. Possibly well-graded. Greatest proportion of contaminants in mass retained on 5 mm sieve.
75GPE1	100	78	64	46	30	11	1	Visual brick:conrete = 15:85 (based on coarse aggregate fraction). Normal "concrete/greyish" colour. Quite a large quantity/proportion of large (>75 mm?) chunks. If >75 mm taken out then probably grading would be of typical 50DP. Predominantly concrete and slightly damp. One large brick chunk (>75mm) and few brick pieces > 20 mm. High number of large pieces of concrete and an apparent low proportion of brick pieces. Appears well graded. Relatively low proportion of contaminants compared with samples previously seen. Greatest proportion of contaminants in mass retained on 5 mm sieve.

Table B.2: Grading and Visual Observation for Samples of Demolition Arisings

Material Code	Grading							Description (based on grading and on at least two independent visual observations)
	Cumulative percent passing sieve size (mm)							
	75	37.5	20	10	5	0.6	0.075	
75GPE2	100	82	69	49	32	11	0	Visual brick:concrete = 15:85 (based on coarse aggregate fraction). Normal "concrete/greyish" colour. quite a large quantity/proportion of large (>75 mm?) chunks. If >75 mm taken out then probably grading would be of typical 50DP. Predominantly concrete and slightly damp. Few brick pieces > 20 mm. High number of large pieces of concrete and an apparent low proportion of brick pieces. Appears well graded. Relatively low proportion of contaminants compared with samples previously seen. Greatest proportion of contaminants in mass retained on 5 mm sieve.
75GPF1	100	81	65	49	30	8	1	Visual brick:concrete = 10:90 (based on coarse aggregate fraction). Self cementing evident even though dry. Normal concrete colour. Large chunks present (mainly concrete). Contaminants in medium range. Large bits of carpet underlay, timber, metal. Medium proportion of contaminants. Grading may fit closer to finer side of type 1sub-base. Moderate amount of contaminants (greater than that of 50DPG2). 75GPF1 has more waste than 75GPF2. A good number of large pieces (no large brick pieces). Low but identifiable proportions of brick in the medium size range. Samples appear reasonably well-graded. Greatest proportion of contaminants in mass retained on 5 mm sieve.
75GPF2	100	78	66	49	30	7	1	Visual brick:concrete = 10:90 (based on coarse aggregate fraction). Self cementing evident even though dry. Normal concrete colour. Large chunks present (mainly concrete). Contaminants in medium range - smaller bits of carpet underlay, timber, metal (compared to 75GPF1). Medium proportion of contaminants. Grading may fit closer to finer side of type 1sub-base. Moderate amount of contaminants (greater than that of 50DPG2). 75GPF1 has more waste than 75GPF2. A good number of large pieces (no large brick pieces). Low but identifiable proportions of brick in the medium size range. Samples appear reasonably well-graded. Greatest proportion of contaminants in mass retained on 5 mm sieve.
75GPG1	100	96	81	46	19	7	1	Visual brick:concrete = 20:80 before air drying (based on coarse aggregate fraction). Appears to have an even spread of concrete and bricks in range 20 to 5 mm (less of breeze blocks). Particle sizes in the range 20 to 5 mm but low proportion of fines relatively compared to 75DPG2. Colour similar to 75DPG2 (i.e. not very grey). Usual set of contaminants. Reasonably well-graded. Not particularly dusty and with relatively small proportions of brick content. Contaminants proportion similar to 75DPG1/75DPG2/75GPG2 and about the same and consistent with previous samples. Greatest proportion of contaminants in mass retained on 5 mm sieve.

Table B.2: Grading and Visual Observation for Samples of Demolition Arisings

Material Code	Grading: Cumulative percent passing sieve size (mm)							Description (based on grading and on at least two independent visual observations)
	75	37.5	20	10	5	0.6	0.075	
75GPG2	100	90	77	49	21	7	0	Visual brick:concrete = 20:80 before air drying (based on coarse aggregate fraction). Appears to have an even spread of concrete and bricks in range 20 to 5 mm (less of breeze blocks). Appears to have high proportion of particle sizes in the range 20 to 5 mm but low proportion of fines relatively compared to 75DPG2. Colour similar to 75DPG2 (i.e. not very grey). Usual set of contaminants. Reasonably well-graded. Not particularly dusty and with relatively small proportions of brick content. Contaminants proportion similar to 75DPG1/75DPG2/75GPG1 and about the same and consistent with previous samples. Greatest proportion of contaminants in mass retained on 5 mm sieve.
75GPH1	100	86	68	51	35	12	1	Visual brick:concrete = 25:75 (based on coarse aggregate fraction) probably difficult to tell because of dark colour hence above ratio very suspect. Appears dry and has slightly dark colour (darker than 75DPH samples) - colour appears to be like plasterboard on day of air drying. Pieces of large chunk present (mainly concrete). appears to have large proportion of fines. May lie closer to upper boundary of type 1. Usual contaminants. A low proportion of brick pieces but this sample is a different colour compared to "concrete" coloured 75GPH2/50DPJ1/50DPJ2. A few large pieces of concrete and a moderate amount of contaminants. Appears to have a lot of fine material. Greatest proportion of contaminants in mass retained on 5 mm sieve.
75GPH2	100	87	76	58	40	13	1	Visual brick:concrete = 15:85 (based on coarse aggregate fraction). Colour similar to 75DPH1 (not as dark as 75GPH1). Particle size distribution similar to 75GPH1 (contains some brick lumps > 37.5 mm). More varied lumps than 75GPH1 (i.e. polyetheylene, plyboard, metals, glass, plastics). Different colour to 75GPH1. This sample also has a few large pieces of material and it has a higher proportion of contaminants. Appears to have a lot of fine material. Greatest proportion of contaminants in mass retained on 5 mm sieve.
75GPJ1	100	94	83	52	27	7	1	Visual brick:concrete = 20:80 before air drying (based on coarse aggregate fraction). Appears to have high proportion in range 20 to 5 mm (single size more or less). Has a high proportion of fines too. Greyish concrete colour. Some large chunks also present - mainly concrete (1 breeze). Brick particles (> 10 mm) also present. High quantity (relatively) of contaminants (essentially timber). Grading may be slightly finer than 75GPG1. Larger amount of contaminants. Few large pieces and there appear to be a large amount in the 10-30 mm size range. Brick proportions higher than 75DPJ1/75DPJ2. Greatest proportion of contaminants in mass retained on 5 mm sieve. Twelve pieces retained on 37.5 mm sieve (1 breeze).

Table B.2: Grading and Visual Observation for Samples of Demolition Arisings

Material Code	Grading							Description (based on grading and on at least two independent visual observations)
	Cumulative percent passing sieve size (mm)							
	75	**37.5**	**20**	**10**	**5**	**0.6**	**0.075**	
75GPJ2	100	96	88	62	37	10	1	Predominantly concrete (based on coarse aggregate fraction). High proportion of fines. Relatively higher proportion of bricks retained on 10 mm Relatively higher proportion of contaminants. Concrete colour. Few coarse aggregates (greater than 37.5 mm) and there appears to be a large proportion in the 10-30 mm size range. Greatest proportion of contaminants retained on 5 mm sieve. Grading curve lies approximately in the middle of the sub-base Type 1 envelope from the 0.6 mm size up to the 10 mm size; other sizes lie nearer the lower limit of Type 1 sub-base. Grading curve lies along the upper (fine) limit of the 75GP envelope.
75GPK1	100	87	70	45	23	5	1	Visual brick:concrete = 20:80 before air drying (based on coarse aggregate fraction). Some large chunks (> 75 mm?) present. Slightly lighter colour than normal grey concrete colour. Some brick present in coarse aggregate fractions. Appears to have relatively low proportion of fines. May fit lower grading of type 1. contaminants - mid-range in proportion and usual stuff. Dry on day of air drying. Moderate amount of contaminants. Very small visible brick content and fine material concrete coloured. Has reasonable amount of large pieces. Greatest proportion of contaminants in mass retained on 5 mm sieve.
75GPK2	100	89	79	58	37	12	1	Visual brick:concrete = 10:90 before air drying (based on coarse aggregate fraction). Normal grey concrete colour. More fines than in 75GPK1. Some large chunks present (similar to 75GPK1). Looks like it may fit slightly closer to middle of type 1 envelope. Not as many coarse brick fractions as 75GPK1. Dry on day of air drying. Usual contaminants (metal & glass also present). Moderate amount of contaminants. Very small visible brick content and fine material is concrete coloured. Has reasonable amount of large pieces. Seems to have rather more amount of fines (compared to 75GPK1/75DPK1/75DPK2). Greatest proportion of contaminants in mass retained on 5 mm sieve.

Table B.3: Summary of grading results for crushed demolition arisings

	Sieve Size (mm)						
	75	**37.5**	**20**	**10**	**5**	**0.6**	**0.075**
	Cumulative percent passing (50DP samples)						
Maximum	100	100	94	79	57	20	1
Minimum	100	85	75	52	33	10	0
Average	100	98	89	67	44	15	1
	Cumulative percent passing (75DP samples)						
Maximum	100	97	89	72	59	34	6
Minimum	100	75	57	40	25	9	0
Average	100	86	72	53	36	14	1
Maximum*	100	97	89	69	46	19	2
Average*	100	86	71	52	35	13	1
	Cumulative percent passing (75GP samples)						
Maximum	100	96	88	62	40	13	1
Minimum	100	75	58	41	19	5	0
Average	100	86	72	51	31	10	1

*Excluding outlier

B.2 Moisture Content-Dry Density Relationship of Construction Arisings

Compaction tests were carried out using CBR moulds (2.3 litres) in accordance with British Standard procedures (British Standards Institution 1990e). Since the arisings were susceptible to crushing, fresh samples of arisings were prepared at different moisture contents. Calculations for wet density and dry density are shown as equations B.1 and B.2. Test results of the relationships between dry density and moisture content are shown as Table B.4.

$$\text{Wet density} = \frac{\text{Compacted mass of wet material}}{\text{Volume of mould}} \qquad \text{B.1}$$

$$\text{Dry density} = \frac{100 \times \text{Wet density}}{100 + \omega} \qquad \text{B.2}$$

Where:

ω = percent moisture content

Table B.4: Density-Moisture Content Relationship in CBR mould

	Sample 1 (vibrating hammer – demolition arisings)					
Sample nr.		1	2	3	4	5
mass of mould + material	g	9391	9335	9523	9404	9447
mass of the mould	g	4867	4867	4867	4867	4867
mass of the material	g	4524	4468	4656	4537	4580
mould diameter	mm	151	151	151	151	151
specimen height	mm	130	127	128	127	130
Volume of the mould	cm^3	2328	2274	2292	2274	2328
Mass of tin	g	10	10	10	10	10
mass of tin + wet material	g	127	138	103	139	149
mass of tin + dry material	g	117	127	93	124	131
Wet density	g/cm^3	1.943	1.965	2.031	1.995	1.967
Moisture Content	%	**9.39**	**9.87**	**12.05**	**13.16**	**15.35**
Dry density	g/cm^3	**1.776**	**1.788**	**1.813**	**1.763**	**1.705**

	Sample 2 (vibrating hammer – demolition arisings)					
Sample nr.		1	2	3	4	5
mass of mould + material	g	9213	9547	9406	9348	9351
mass of the mould	g	4867	4867	4867	4867	4867
mass of the material	g	4346	4680	4539	4481	4484
mould diameter	mm	151	151	151	151	151
specimen height	mm	130	130	128	128	132
Volume of the mould	cm^3	2328	2328	2292	2292	2364
mass of tin	g	10	10	10	10	10
mass of tin + wet material	g	135	138	149	158	167
mass of tin + dry material	g	127	127	134	141	147
Wet density	g/cm^3	1.867	2.010	1.980	1.955	1.897
Moisture Content	%	**6.87**	**9.87**	**12.10**	**12.98**	**15.02**
Dry density	g/cm^3	**1.747**	**1.830**	**1.766**	**1.730**	**1.649**

	Sample 3 (vibrating hammer – demolition arisings)					
Sample nr.		1	2	3	4	5
mass of mould + material	g	9308	9346	9526	9531	9500
mass of the mould	g	4867	4867	4867	4867	4867
mass of the material	g	4441	4479	4659	4664	4633
mould diameter	mm	151	151	151	151	151
specimen height	mm	130	128	129	130	131

Table B.4: Density-Moisture Content Relationship in CBR mould

Volume of the mould	cm^3	2328	2292	2310	2328	2346
mass of tin	g	10	10	10	10	10
mass of tin + wet material	g	126	166	145	167	178
mass of tin + dry material	g	116	152	130	149	155
Wet density	g/cm^3	1.908	1.954	2.017	2.003	1.975
Moisture Content	%	**9.43**	**9.89**	**12.08**	**13.36**	**16.26**
Dry density	g/cm^3	**1.743**	**1.778**	**1.799**	**1.767**	**1.699**

	Sample 4 (4.5 kg rammer – roadway arisings)					
Sample nr.		1	2	3	4	5
mass of mould + material	g	9691	9899	10026	9896	9855
mass of the mould	g	4867	4867	4867	4867	4867
mass of the material	g	4824	5032	5159	5029	4988
mould diameter	mm	150.2	150.2	150.2	150.2	150.2
specimen height	mm	130	130	130	130	130
Volume of the mould	cm^3	2303	2303	2303	2303	2303
mass of tin	g	982	981	977	974	986
mass of tin + wet material	g	1626	1821	1821	1854	1924
mass of tin + dry material	g	1600	1772	1752	1773	1814
Wet density	g/cm^3	2.094	2.185	2.240	2.183	2.165
Moisture Content	%	**4.21**	**6.19**	**8.90**	**10.14**	**13.29**
Dry density	g/cm^3	**2.010**	**2.057**	**2.057**	**1.982**	**1.912**

	Sample 5 (4.5 kg rammer – roadway arisings)					
Sample nr.		1	2	3	4	5
mass of mould + material	g	9432	9615	9937	9907	9825
mass of the mould	g	4866	4866	4867	4867	4867
mass of the material	g	4566	4749	5070	5040	4958
mould diameter	mm	150.2	150.2	150.2	150.2	150.2
specimen height	mm	130	130	130	130	130
Volume of the mould	cm^3	2303	2303	2303	2303	2303
mass of tin	g	982	981	977	974	986
mass of tin + wet material	g	1523	1898	1843	1859	1866
mass of tin + dry material	g	1503	1859	1776	1772	1784
Wet density	g/cm^3	1.982	2.062	2.201	2.188	2.152
Moisture Content	%	**3.84**	**4.44**	**8.39**	**10.90**	**10.28**
Dry density	g/cm^3	**1.909**	**1.974**	**2.031**	**1.973**	**1.952**

Table B.4: Density-Moisture Content Relationship in CBR mould

		Sample 6 (4.5 kg rammer – roadway arisings)				
Sample nr.		1	2	3	4	5
mass of mould + material	g	9663	9810	9873	9909	9831
mass of the mould	g	4866	4866	4866	4866	4867
mass of the material	g	4797	4944	5007	5043	4964
mould diameter	mm	150.2	150.2	150.2	150.2	150.2
specimen height	mm	130	130	130	130	130
Volume of the mould	cm^3	2303	2303	2303	2303	2303
mass of tin	g	982	981	977	974	986
mass of tin + wet material	g	1881	1881	1855	1822	1870
mass of tin + dry material	g	1846	1829	1794	1752	1768
Wet density	g/cm^3	2.083	2.146	2.174	2.189	2.155
Moisture Content	%	**4.05**	**6.13**	**7.47**	**9.00**	**13.04**
Dry density	g/cm^3	**2.001**	**2.022**	**2.023**	**2.009**	**1.906**

Test results of the relationships between dry density and moisture content are shown as Table B.4.

B.3 CBR of Construction Arisings

The laboratory CBR test is a standard load–penetration type test that involves driving a plunger of standard dimensions into a cylindrical mould of the recompacted material at a standard rate and measuring the load required to cause penetrations at standard intervals. The sample can be inverted and the process of penetration repeated. Annular (surcharge) weights can be used to simulate the effect of the overlying pavement layers on the CBR. Loads causing penetrations of 2.5 mm and 5.0 mm are compared with loads causing similar penetrations of a standard well-graded fine crushed limestone rock (first standardized in California); the CBR of the standard crushed rock is 100%. A correction may be required if the initial part of the curve is concave upwards, as shown in Figure B.1. A tangent at the point of greatest slope, i.e. the point of inflexion is drawn and produced until it intersects the penetration axis. The corrected curve origin is the point from which the new penetration scale can be marked.

The force-penetration relationship of the standard crushed rock is shown as Table B.5. Equation B.3 is used to determine the CBR; expressed as a percentage of the corresponding standard crushed rock loads.

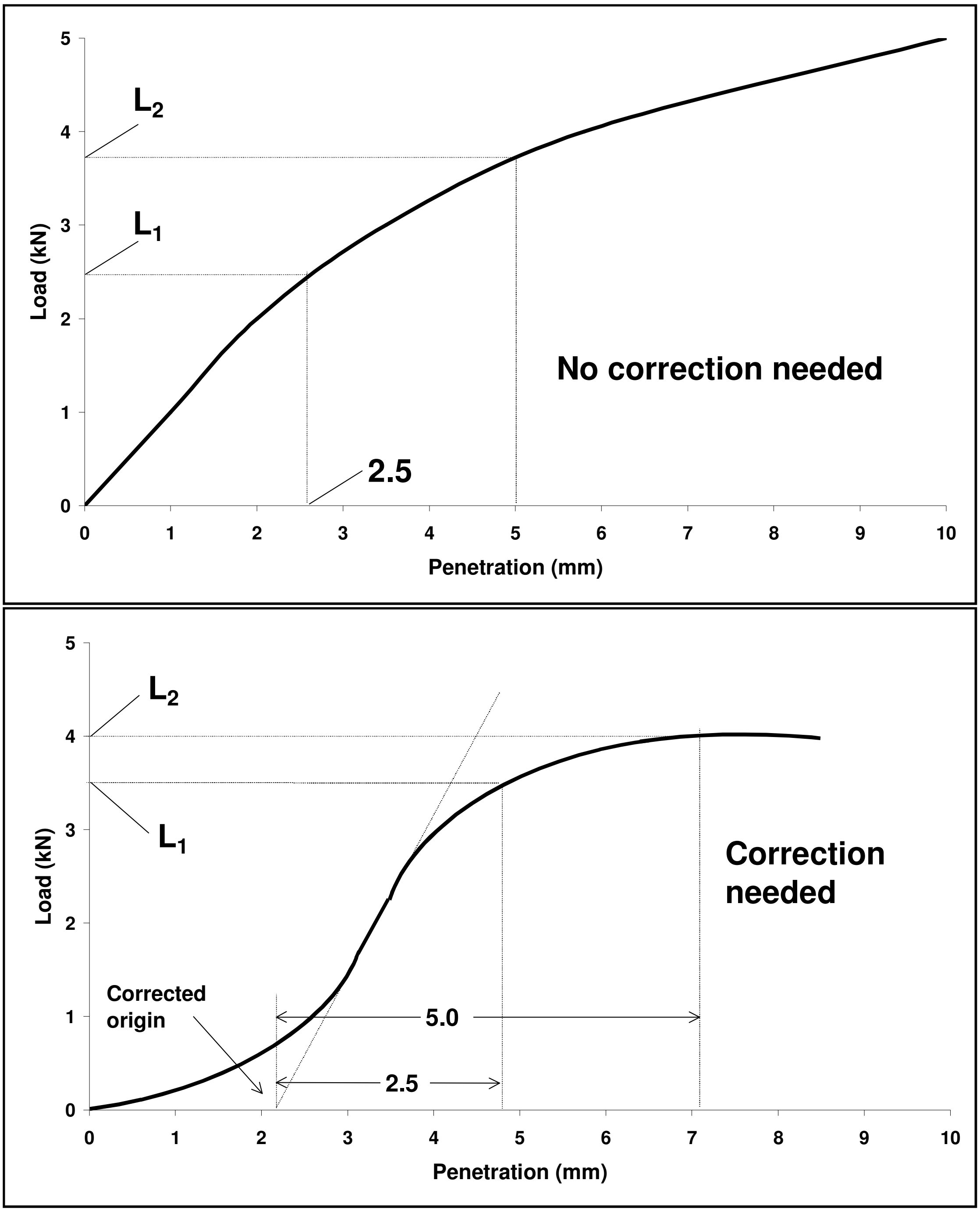


Figure B.1: Hypothetical CBR test results (not to scale)

Table B.5: Standard force-penetration relationships for 100 % CBR

Load (kN)	11.50	**13.24**	17.60	**19.96**	22.20	26.30	30.30	33.50
Penetration (mm)	2.0	**2.5**	4.0	**5.0**	6.0	8.0	10.0	12.0

$$CBR\ (\%) = \frac{100 \times L_1}{13.24} \text{ or } \frac{100 \times L_2}{19.96} \qquad \text{B.3}$$

(whichever is greater)

Where:

L_1 = Load applied (kN) on the sample at a penetration of 2.5 mm

L_2 = Load applied (kN) on the sample at a penetration of 5 mm

(L_1 and L_2 are considered at penetrations higher than 2.5 mm and 5 mm, respectively, if the initial part of the curve is concave upwards, as shown in Figure B.1).

Table B.6 to Table B.7 and Figure B.2 to Figure B.8 shows the CBR test results.

Table B.6: CBR test results – demolition arisings

Sample 1 (moisture content = 12%)		Sample 2 (moisture content = 9.9%)		Sample 3 (moisture content = 12.1%)	
Penetration (mm)	**Plunger load (kN)**	**Penetration (mm)**	**Plunger load (kN)**	**Penetration (mm)**	**Plunger load (kN)**
0.00	0.000	0.00	0.000	0.00	0.000
0.25	0.148	0.25	1.628	0.25	1.157
0.50	0.573	0.50	3.470	0.50	2.870
0.75	1.238	0.75	5.098	0.75	4.969
1.00	2.218	1.00	6.426	1.00	6.555
1.25	3.234	1.25	7.454	1.25	7.583
1.50	4.435	1.50	8.182	1.50	8.354
1.75	5.729	1.75	9.082	1.75	9.082
2.00	6.745	2.00	9.939	2.00	10.025
2.25	7.466	2.25	10.753	2.25	10.753
2.50	8.076	**2.50**	**11.395**	**2.50**	**11.310**
2.75	8.686	2.75	12.638	2.75	11.781
3.00	**9.222**	3.00	13.495	3.00	12.595
3.25	9.647	3.25	14.180	3.25	13.258
3.50	10.072	3.50	14.823	3.50	13.923
3.75	10.718	3.75	15.337	3.75	14.694

Table B.6: CBR test results – demolition arisings

Sample 1 (moisture content = 12%)		Sample 2 (moisture content = 9.9%)		Sample 3 (moisture content = 12.1%)	
Penetration (mm)	**Plunger load (kN)**	**Penetration (mm)**	**Plunger load (kN)**	**Penetration (mm)**	**Plunger load (kN)**
4.00	10.903	4.00	16.065	4.00	15.294
4.25	11.273	4.25	16.793	4.25	15.722
4.50	11.642	4.50	17.436	4.50	16.750
4.75	12.252	4.75	18.121	4.75	17.350
5.00	12.770	**5.00**	**18.935**	**5.00**	**18.079**
5.25	13.084	5.25	19.664	5.25	19.021
5.50	**13.657**	5.50	20.435	5.50	19.664
5.75	14.193	5.75	21.163	5.75	20.178
6.00	14.710	6.00	21.720	6.00	20.455
6.25	15.154	6.25	22.620	6.25	21.334
6.50	15.616	6.50	23.219	6.50	22.405
6.75	15.874	6.75	23.948	6.75	23.305
7.00	16.133	7.00	24.633	7.00	23.990
7.25	16.540	7.25	25.147	7.25	24.719
7.50	16.724	7.50	25.704	7.50	25.447

Table B.7: CBR test results – roadway arisings

Sample 4 (moisture content = 8.4%)		Sample 5 (moisture content = 8.37%)		Sample 6 (moisture content = 7.57%)	
Penetration (mm)	**Plunger load (kN)**	**Penetration (mm)**	**Plunger load (kN)**	**Penetration (mm)**	**Plunger load (kN)**
0.00	0.000	0.00	0.000	0.00	0.000
0.25	0.643	0.25	0.171	0.25	0.364
0.50	1.756	0.50	0.600	0.50	1.007
0.75	3.427	0.75	1.371	0.75	2.099
1.00	5.012	1.00	2.485	1.00	3.127
1.25	6.469	1.25	3.813	1.25	4.198
1.50	7.497	1.50	5.226	1.50	5.226
1.75	8.397	1.75	6.555	1.75	6.040
2.00	8.782	2.00	7.583	2.00	6.769
2.25	9.296	2.25	8.439	2.25	7.476
2.50	**9.960**	2.50	9.189	**2.50**	**8.097**
2.75	10.517	2.75	9.789	2.75	8.697
3.00	11.053	**3.00**	**10.410**	3.00	9.211
3.25	11.545	3.25	10.924	3.25	9.703
3.50	11.867	3.50	11.460	3.50	10.239
3.75	12.231	3.75	11.952	3.75	10.689
4.00	12.574	4.00	12.338	4.00	11.074
4.25	12.852	4.25	12.595	4.25	11.545
4.50	13.152	4.50	13.023	4.50	11.952
4.75	13.473	4.75	13.366	4.75	12.381

Table B.7: CBR test results – roadway arisings

Sample 4 (moisture content = 8.4%)		Sample 5 (moisture content = 8.37%)		Sample 6 (moisture content = 7.57%)	
Penetration (mm)	**Plunger load (kN)**	**Penetration (mm)**	**Plunger load (kN)**	**Penetration (mm)**	**Plunger load (kN)**
5.00	13.837	5.00	13.773	5.00	12.831
5.25	14.223	5.25	14.223	5.25	13.283
5.50	14.566	5.50	14.608	5.50	13.645
5.75	14.951	5.75	14.973	5.75	14.052
6.00	15.251	6.00	15.358	6.00	14.394
6.25	15.444	6.25	15.722	6.25	14.737
6.50	15.744	6.50	16.044	6.50	15.080
6.75	16.108	6.75	16.408	6.75	15.358
7.00	16.408	7.00	16.708	7.00	15.722
7.25	16.772	7.25	17.007	7.25	16.129
7.50	17.050	7.50	17.329	7.50	16.536

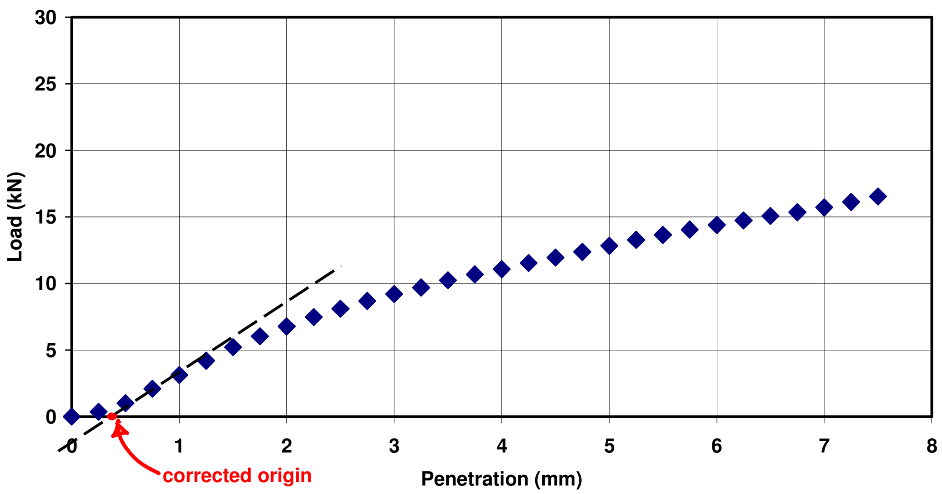


Figure B.2: CBR plot for sample 1 – demolition arisings

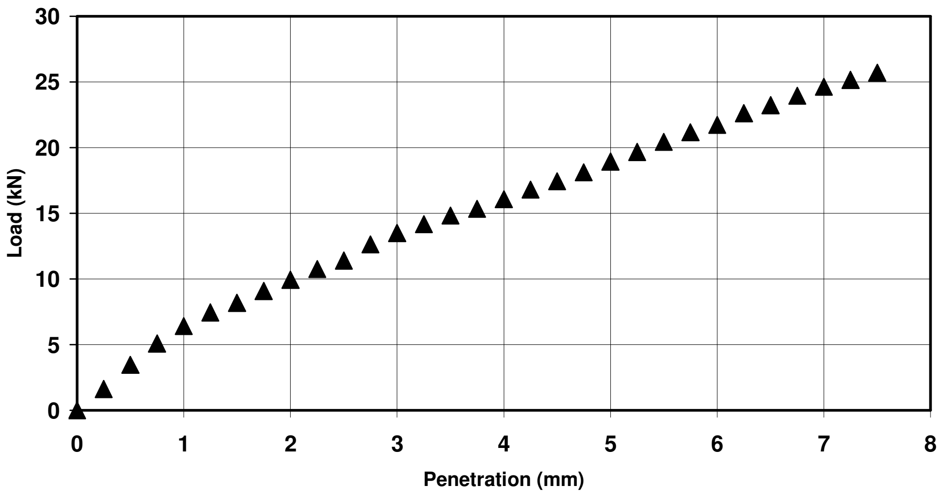


Figure B.3: CBR plot for sample 2 – demolition arisings

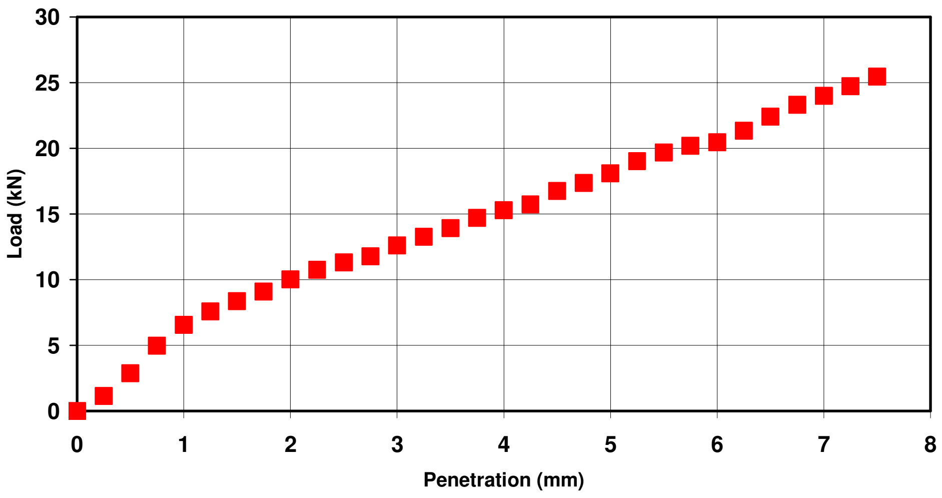


Figure B.4: CBR plot for sample 3 – demolition arisings

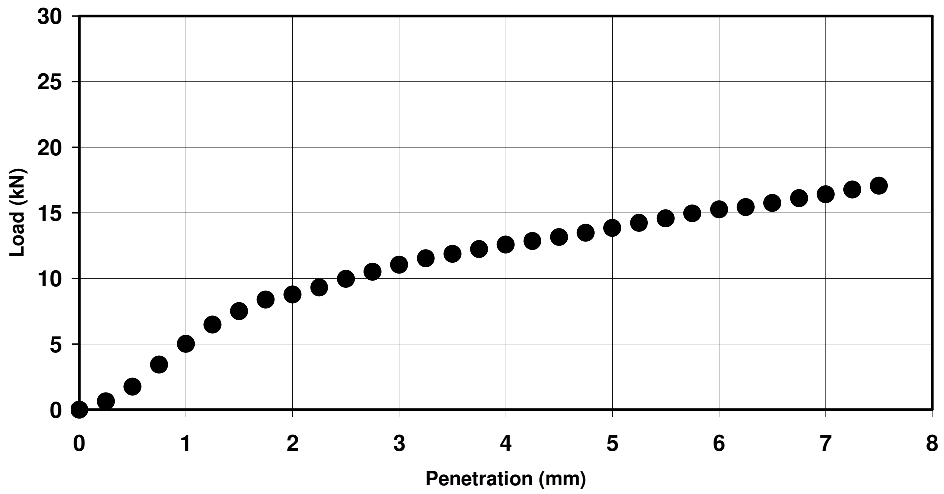


Figure B.5: CBR plot for sample 4 – roadway arisings

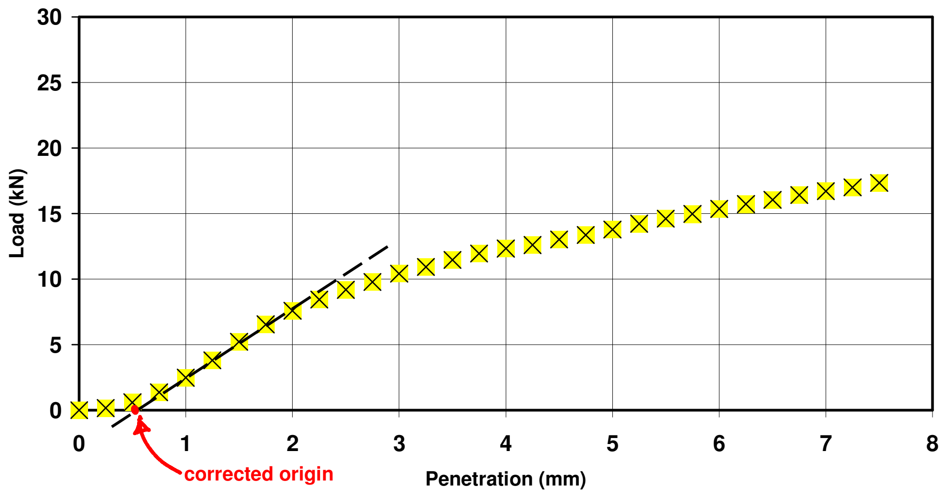


Figure B.6: CBR plot for sample 5 – roadway arisings

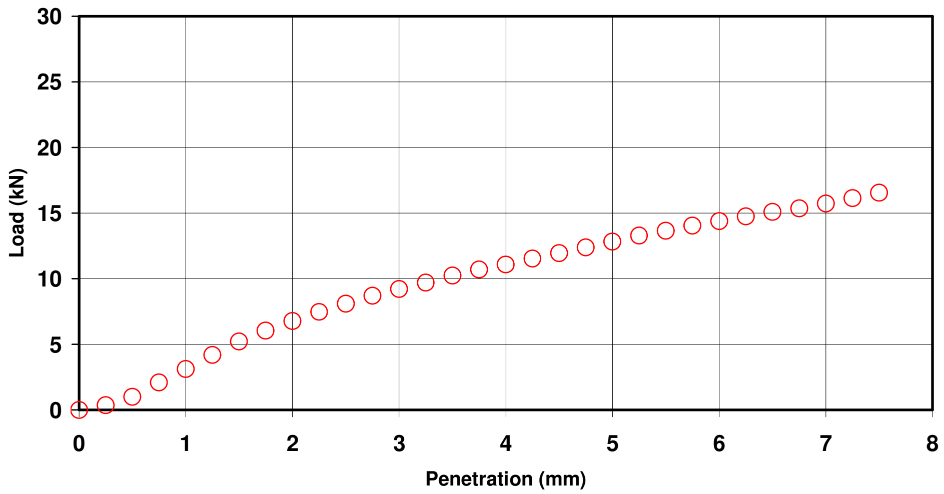


Figure B.7: CBR plot for sample 6 – roadway arisings

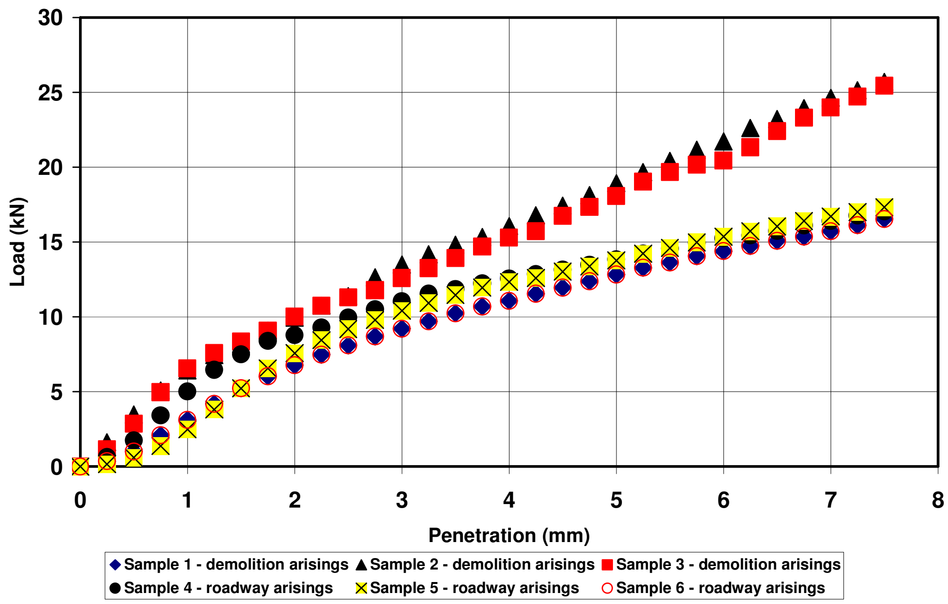


Figure B.8: CBR plot for all samples

CBR values are given in Table B.8, calculated using equation B.3.

Table B.8: CBR calculations

Sample description	CBR (%)	average CBR (%)
Sample 1 - demolition arisings	70	
Sample 2 - demolition arisings	95	
Sample 3 - demolition arisings	91	85
Sample 4 - roadway arisings	75	
Sample 5 - roadway arisings	79	
Sample 6 - roadway arisings	64	73

Appendix C Publications

Variation in Particle Size Distribution from Primary Crushing of Demolition Waste

By

O I Ogwuda, D Fordyce and J Underwood (1998)

in Sustainable Construction: Use of Recycled Concrete Aggregate

(edited by R K Dhir, N A Henderson and M C Limbachiya) pp 121-133

ABSTRACT. This work investigates the variability in particle size distribution of sixty samples of demolition waste produced by different primary crushing processes. The demolition waste consisted of mainly concrete, clay bricks and clinker (breeze) blocks with concrete forming most of the waste. The results indicate that the particle size distribution curves are consistently well-graded, not significantly variable and similar to British specification for sub-base Type 1 material in spite of the variable nature of the demolition waste and the unsophisticated primary crushing processes (compared to quarry processes). With good control during the demolition and primary crushing processes consistent demolition waste can be produced. The work forms part of an overall research investigation to assess the load-bearing and durability characteristics of demolition wastes for use in road pavements.

Keywords: Demolition Waste, Jaw Crusher, Particle Size Distribution, Primary Crushing, Recycled Aggregate, Road Pavement, Sub-base.

Introduction

The use of recycled concrete aggregate in construction is not a new concept, and is well documented [1,2]. Unbound recycled concrete aggregate can be used as fill in drainage, as general bulk fill, and as base material in road construction. Cement bound and bituminous mixtures can consist of recycled concrete aggregate but this is relatively more restrictive due to problems arising from contaminants in the recycled aggregates and inherent chemical reactions that may affect the binder or the mixture.

An important property in determining the suitability of recycled concrete aggregate is the particle size distribution. Although the effect of particle size distribution of recycled concrete aggregate on the properties of unbound or bound mixtures can be readily understood, there is little information on the variation in particle size distribution arising from primary crushing processes.

Most organisations involved in the use of primary jaw crushers tend to give typical particle size distributions.

The demolition of two 17-storey residential blocks in the Ardler area of Dundee has recently been completed. Particle size distribution tests were carried out on sixty samples of the crushed demolition waste produced by three different primary crushing processes. The results indicate that the particle size distribution curves are consistently well-graded, are similar in shape to British specifications [3] for road pavement granular sub-base (Type 1), and are not, in general, significantly variable. This is in spite of the very unsophisticated crushing methods (compared to quarry processes for natural aggregates) and the variable nature of the constituents of the demolition waste.

Preliminary conclusions are that with good control during the demolition waste production processes a consistent product is possible from primary crushing of demolition waste.

Production of Crushed Demolition Waste

Demolition

The demolition process included stripping out of the building (ie removal of timber frames and flooring, doors, plasterboard, asbestos, glass windows, wall paper, etc), pre-weakening of the building skeleton, followed by controlled blow down of the building using explosives. The rubble was not distinctly separated into different constituent materials because of the method of blow down employed.

Crushing and Screening

Prior to crushing it would have been desirable to separate the concrete rubble from the other constituents of the demolition waste but this was not possible for economic reasons. Two different single toggle jaw crushers (both mobile) were used to crush the demolition rubble. Oversized demolition rubble pieces were broken down using hydraulic impact hammers before being fed into the jaw crushers. Each jaw crusher had overband magnetic separators situated above the discharge conveyors to remove ferrous materials (mainly steel reinforcement). The crushed demolition waste was produced using three different processes:

1. METHOD 1 - crushed demolition waste was produced in one pass through the jaw crusher with the closed side setting at 75 mm (75 mm nominal maximum particle size). Samples produced by this method were assigned codes starting with the digits 75DP.
2. METHOD 2 - crushed demolition waste was produced in one pass through the jaw crusher (closed side setting at 75 mm), and subsequently one pass through a single 50 mm screen (50 mm nominal maximum particle size). Samples produced by this method were assigned codes starting with the digits 50DP.
3. METHOD 3 - crushed demolition waste was produced in one pass through the jaw crusher with the closed side setting at 75 mm (75 mm nominal maximum particle size). Fines were taken out via the grizzly fines chute and side discharge conveyor prior to crushing. Samples produced by this method were assigned codes starting with the digits 75GP.

(The same jaw crusher was used for METHODS 1 and 2, while a different jaw crusher was used for METHOD 3).

Demolition Waste Materials

The crushed demolition waste (approximately 60,000 tonnes) consisted of mainly concrete, clay bricks and clinker (breeze) blocks, with concrete forming most of the waste. Small amounts of “contaminants” in the demolition wastes consisted of mainly timber plus smaller proportions of plastics, metal and glass. The proportion of “contaminants” were fairly low and on average did not exceed 5% (approximately) by volume. Figure 1 shows typical materials of the demolition waste.

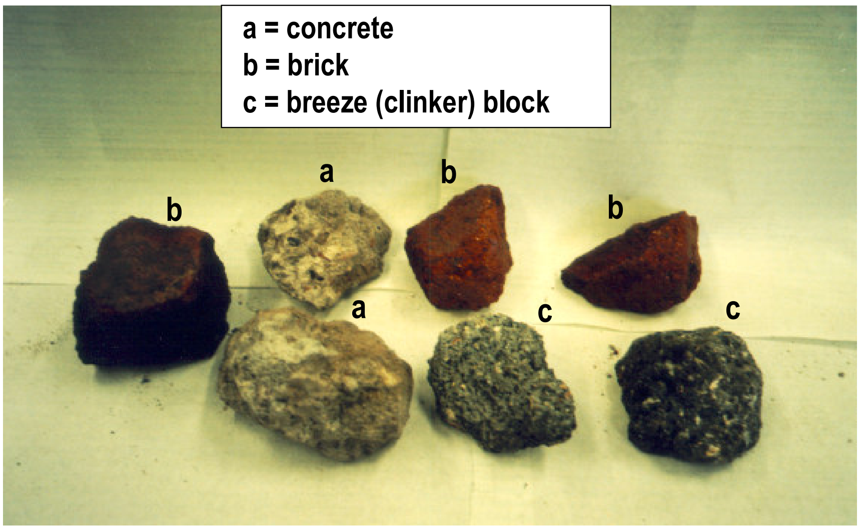


Figure 1 Typical materials in demolition waste (37.5 mm nominal particle size)

Sampling

In top-loading stockpiles, as was the case on this site, there is the tendency for segregation with coarse aggregate fractions remaining on the outside and near the bottom. At the same time fine aggregate particles are filtered through the void spaces of the coarser aggregate. These concerns were taken into account when samples were collected on each occasion. Samples were taken from all stockpiles on the demolition site based on guidelines given elsewhere [4,5]. Samples were collected under differing weather conditions.

Sixty samples with an average mass of approximately 30 kg were collected. The samples were split into groups based on the method of production. A summary of the samples collected is given in Table 1.

Laboratory Work

A 500 mm diameter mechanical sieve shaker (Figure 2) was used to determine the particle size distribution of all sixty samples. The sieve sizes used were 75 mm, 37.5 mm, 20 mm, 10 mm, 5 mm, 0.6 mm and 0.075 mm - these sizes correspond to British specifications for road pavement unbound granular sub-bases [3]. The visual appearance of the demolition waste indicated that there were no materials which would cause aggregation of particles, hence dry sieving was adopted.

Figure 2 Mechanical Sieve Shaker

Table 1 Summary of Demolition Waste Samples Collected

METHOD OF PRODUCTION (see section on Crushing and Screening)	SAMPLE GROUP CODE	NUMBER OF SAMPLES
METHOD 1	75DP	20
METHOD 2	50DP	20
METHOD 3	75GP	20

Results and Discussion

Visual Assessment

Visual assessments of constituent material proportions in the demolition waste were not completely possible as it was difficult to distinguish the constituents in the fine aggregate fractions. Visual assessment, based on coarse aggregate fractions only, did not indicate any direct relationship between particle size distribution and proportion of constituent materials (bricks, concrete and breeze blocks) irrespective of the processing method employed in crushing the demolition waste. For example, within the same sample group (e.g. 50DP samples only) a sample with a relatively high proportion of bricks could give a coarser grading and in other instances a sample with a relatively high proportion of concrete could give a finer grading.

Sample group comparisons (e.g. 50DP-75DP comparisons) of particle size distribution give an even more random picture.

One explanation for the difficulty in relating visual assessment to particle size distribution could be the different strengths of concrete [6], and different types of bricks contained in the demolition waste. Also visual assessments are based on proportions of constituent materials in coarser aggregate fractions only, which may not necessarily be the same as the proportions of constituent materials in the finer aggregate fractions. In addition the ranges of particle size distributions appear not to be large enough to comment confidently on the effects of constituent materials on particle size distribution. If the demolition waste had been separated into distinct constituent materials (ie concrete, bricks and blocks) then the particle size distribution curves may have reflected distinct differences - coarse grading for crushed concrete and finer grading for crushed brick.

Visual particle size distribution assessments of the unsieved samples containing higher quantities of fines can be misleading with the tendency to err on the finer side of the true particle size distributions. This observation may also hold true for large stockpiles of demolition waste on various sites. Segregation occurring from top-loading stockpiles (as pointed out earlier) may lead to this visual error.

Overview of Results

It may be worth noting here that the constituent materials of the demolition waste in all samples are essentially the same, albeit in varied proportions, even though different crushing processes have been used for each sample group. To enable a comparison to be made with British specifications, particle sizes greater than 75 mm were not included in the particle size distribution analysis. For the 75DP and 75GP samples the quantity of particle sizes exceeding 75 mm was on average about 2% of the total mass. Most of the crushed demolition waste retained on the 75 mm sieve was concrete suggesting that clay bricks and clinker blocks were more readily crushed into smaller particle sizes than concrete. As expected, nothing was retained on the 75 mm sieve for the 50DP samples.

Figure 3 shows the particle size distribution envelope for all the samples together with the upper (fine) and lower (coarse) limits of the British specification envelopes for road pavement sub-bases. Figure 4 gives the corresponding average particle size distributions. One of the 75DP samples has been termed an “outlier”. For this sample, in the finer range of particle sizes (less than 5 mm) the distribution curve is considerably at variance with other samples; at the coarser end of the curve this is not the case. A visual assessment of this sample shows a marked difference (eg colour, constituents) to the other samples. Hence based on statistical analysis [7] and visual assessment the sample has been referred to as an “outlier”. Figure 3 and Figure 4 also show the particle size distribution envelope and average particle size distributions for all 75DP samples excluding the “outlier”. None of the other samples was considered to be an outlier based on statistical analysis and visual appearance. The reason for this “outlier” sample is unclear but one explanation could be that the sample did not come from the same population (ie the Ardler multi-storey buildings) as the other samples.

75DP Samples

The particle size distribution curves for these samples were well-graded. Exclusion of the outlier sample in the particle size distribution analysis has no significant effect on the average grading but there is a downward shift of the upper (fine) boundary of the envelope in the smaller particle sizes. Excluding the outlier, the variations in particle size distribution were greatest in the percents passing the 20 mm sieve size (range of 32%) and the variation is progressively smaller as the particle size reduces. The general shape of the particle size distribution curves was concave upwards going from the smallest particle size followed by a slight curvature in the other direction at about the 20 mm particle size. The average particle size distribution (Figure 4) is a typical representation of the shape of the curves.

50DP Samples

The particle size distribution curves for these samples were well-graded. The variations in particle size distribution were greatest in the percents passing the 10 mm sieve size (range of 27%) and the variation is progressively smaller on either side of this sieve size. The general shape of the particle size distribution curves was similar to the 75DP samples. The average particle size distribution (Figure 4) is a typical representation of the shape of the curves.

75GP Samples

The particle size distribution curves for these samples were well-graded. The variations in particle size distribution were greatest in the percent passing the 20 mm sieve size (range of 30%) and the variation is progressively smaller as the particle size reduces. The general shape of the particle size distribution curves was similar to the 75DP samples. The average particle size distribution (Figure 4) is a typical representation of the shape of the curves.

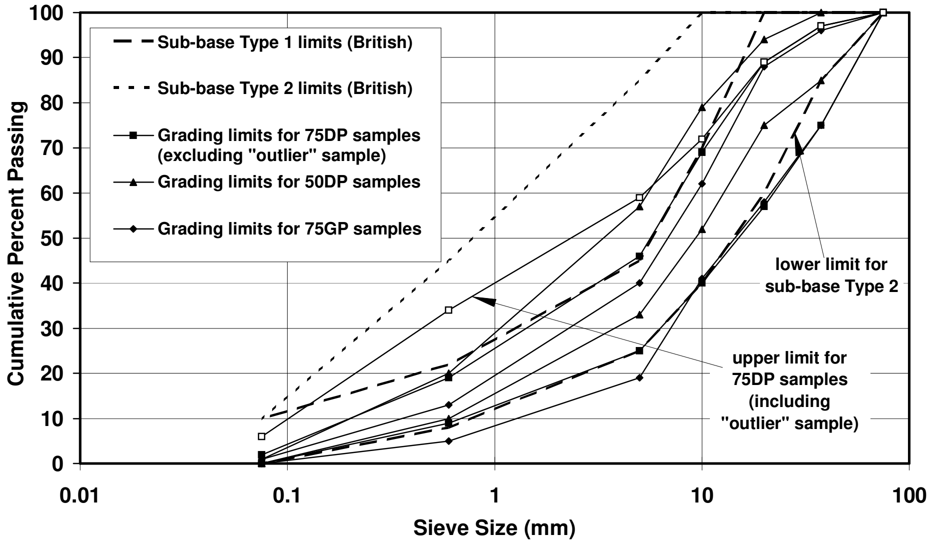


Figure 3 Particle Size Distribution Envelope for Demolition Waste Samples

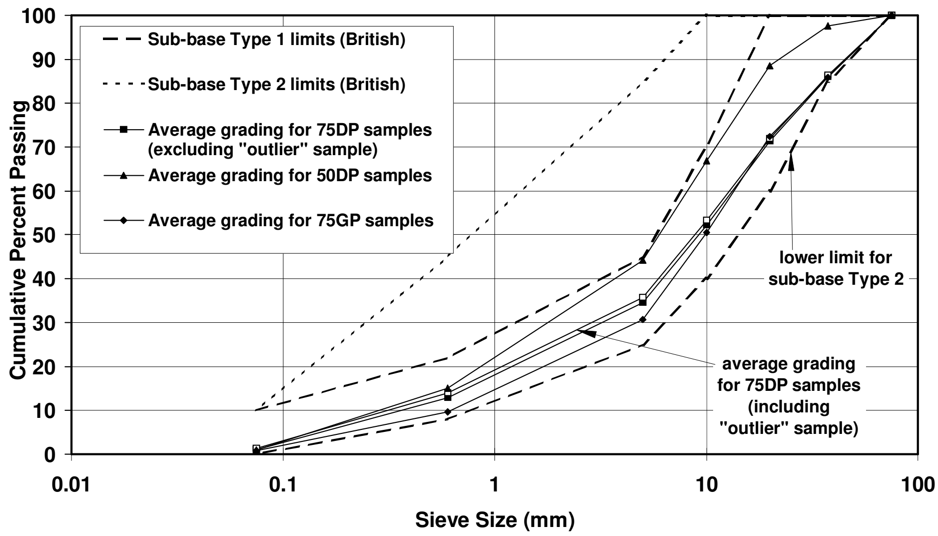


Figure 4 Average Particle Size Distribution for Demolition Waste Samples

All Samples

From Figure 3 it can be seen that there are overlaps in the particle size distribution envelopes for all three samples towards the larger particle sizes, with the envelopes tending to converge and coincide towards the smaller particle sizes. The same observation applies if the mean grading of the 50DP samples is compared with the mean grading for the 75DP or 75GP samples (Figure 4). There is a divergence between the mean gradings of the 75DP and 75GP samples towards the smaller particle sizes and a convergence towards the larger particle sizes. As expected, the 75GP samples tend to have a coarser particle size distribution than the 75DP samples in the smaller particle sizes but in the larger particle sizes their distributions are similar. The 50DP samples have the uppermost (finer) particle size distribution envelope while the 75GP samples have the lowermost (coarser) envelope - the same is true for the mean gradings of the samples.

Comparison with British Specifications for Road Pavement Unbound Granular Sub-bases

The requirements for particle size distribution given in the British Specifications (Table 2) were based on past experiences obtained with mainly primary aggregates. Hence a comparison with the British specification should not necessarily be a basis for accepting or rejecting demolition waste material since the limits given in the specification may not be applicable to demolition wastes and also because particle size distribution on its own cannot be used as a performance indicator. The specification limits can however be used as a reference guide to compare particle size distributions of crushed waste samples produced by different processes.

The British specifications [3] gives two types of unbound granular road pavement sub-bases - Type 1 and Type 2. Sub-base Type 1 is considered to be free-draining, and of superior quality to sub-base Type 2 in terms of materials and restriction on variation in grading. In addition, sub-base Type 1 material has higher strength and stiffness [8]. Sub-base Type 1 is usually specified for heavily trafficked roads and sub-base Type 2 for less trafficked roads.

Table 2 British Specification for Road Pavement Unbound Granular Sub-bases - Particle Size Distribution [3]

Sieve Size (mm)	Percent Passing (Type 1)	Percent Passing (Type 2)
75	100	100
37.5	85 - 100	85 - 100
20	60 - 100	60 - 100
10	40 - 70	40 - 100
5	25 - 45	25 - 85
0.6	8 - 22	8 - 45
0.075	0 - 10	0 - 10

From Figure 4 it can be seen that all the mean particle size distributions fall within the sub-base Type 1 (and Type 2) envelope. Hence it may be argued that the typical representation of the particle size distribution of all the samples falls within the British specifications.

The particle size distribution curves for the 50DP samples are generally spread from the upper to middle of the sub-base Type 1 envelope (Figure 3) with some of the curves lying partially above the envelope. The particle size distribution curves for the 75DP samples (excluding the outlier) are generally spread from the middle to lower limit of the sub-base Type 1 envelope with some of the curves lying partially below or above the envelope. The particle size distribution curves for the 75GP samples are spread in similar manner to the 75DP samples with some of the curves lying partially below the envelope and generally having a coarser grading in the smaller particle sizes (less than 5 mm). None of the particle size distribution curves lie above the sub-base Type 2 envelope.

Table 3 gives a comparison summary between the particle size distribution of the demolition waste samples and the British specifications (Table 2) for sub-bases. Table 3 shows that 45% of the 50DP samples fall outside the specifications for sub-base Type 1 material as a result of the percent passing the 5 mm sieve. Table 3 also shows that 45% of the 75DP and 75GP samples fall outside the specifications as a result of the percent passing the 37.5 mm sieve size. An interesting point to note, is that the particle size distribution curves have the greatest variability (as mentioned earlier) at the percents passing the 10 mm sieve (50DP samples) and 20 mm sieve (75DP and 75GP samples). Hence, the particle size which predominantly falls outside the British specifications, for sub-base Type 1, may not necessarily correspond to the particle size yielding the greatest variation in particle size distributions. From Table 3 the other particle sizes outwith the specifications that may be worth noting are percents passing the 10 mm sieve (50DP samples only), the 5 mm sieve (75DP and 75GP) and 0.6 mm sieve (75GP samples). At least 20% of the samples in each of the sample groups fall outside the specifications for the percent passing the 5 mm sieve.

Practical Application of Results

The results of this work have shown that with good site control it is possible to produce consistent crushed demolition waste material by using an ordinary primary jaw crusher. Some of the necessary factors for good control are crusher settings, wear and tear of the crusher jaws and the screening process used after crushing. The process of production of demolition waste described in this paper is more economical than quarry processes but the outputs in terms of particle size distribution are quite similar. The quarry processes [4] may include crushing at three or more stages, screening (screens used at various stages in the processes and may be single or multiple screens) and blending; the processes mentioned in this paper involve, mainly, the use of only a primary jaw crusher and, optionally, screening.

The variation in particle size distribution of the demolition waste does not seem to be adversely affected by climatic conditions because the crushing operations were carried out from winter to spring.

Table 3 Summary of Demolition Waste Samples in Comparison with British Specifications [3] for Sub-bases - based on Particle Size Distribution (Cumulative Percent Passing)

Sieve Size (mm)	Sample Group	Number of Samples	Percent above Type 2 (%)	Percent above Type 1 (%)	Percent below Type 1 and 2 (%)
75	50DP	20	0	0	0
	75DP	20	0	0	0
	75GP	20	0	0	0
37.5	50DP	20	0	0	0
	75DP	20	0	0	45
	75GP	20	0	0	45
20	50DP	20	0	0	0
	75DP	20	0	0	5
	75GP	20	0	0	5
10	50DP	20	0	35	0
	75DP	20	0	5	0
	75GP	20	0	0	0
	50DP	20	0	45	0

Table 3 Summary of Demolition Waste Samples in Comparison with British Specifications [3] for Sub-bases - based on Particle Size Distribution (Cumulative Percent Passing)

Sieve Size (mm)	Sample Group	Number of Samples	Percent above Type 2 (%)	Percent above Type 1 (%)	Percent below Type 1 and 2 (%)
5	75DP	20	0	20	0
	75GP	20	0	0	20
	50DP	20	0	0	0
0.6	75DP	20	0	5	0
	75GP	20	0	0	30
	50DP	20	0	0	0
0.075	75DP	20	0	0	0
	75GP	20	0	0	0

Jaw crushing and subsequent single screening of demolition waste at a closed side setting (75 mm) to screen size ratio of 1.5 tends to produce a finer grading (at the coarse aggregate end) than crushed demolition waste produced by jaw crushing only. As expected, removal of fines prior to jaw crushing the demolition waste tends to produce a coarser grading than jaw crushing with no fines removal. Hence in the production of crushed demolition waste, jaw crushing operations on site can be adjusted to produce a finer or coarser grading depending on different requirements. It is important to obtain the correct particle size distribution design because this can affect the structural performance of unbound granular materials in road pavements [8,9].

The maximum variation in particle size distribution has a spread of approximately 30%. This variation is based on a single processing method and on variable proportions of constituent materials. If the demolition waste were separated into distinct constituent materials (ie concrete, bricks and blocks) prior to crushing then the spread is likely to be reduced.

The California Bearing Ratio (CBR) is a well known parameter that gives an indication of the bearing capacity of unbound granular pavement foundation materials. As a rule of thumb, on heavily trafficked roads in Britain the minimum CBR for sub-bases should be 30%. The Notes of Guidance [10] which accompany the British specifications for highway works suggests that if at least 10% of the material is greater than 20 mm then the CBR should be greater than 30%. Hence from the particle size distribution results it may be possible to state that the CBR values should be in excess of 30% (75DP and

75GP samples only). Limited CBR tests on this particular demolition waste and CBR tests on other demolition waste have revealed CBR values in excess of 30% [11,12]. More CBR tests are planned which should give better confidence in understanding the relationship between particle size distribution and CBR.

Conclusions

1. The general shapes of the particle size distribution curves are similar irrespective of the processing method employed and the variable constituents of the demolition waste.

2. The shapes of the particle size distribution curves for all samples are generally similar to British specification for sub-base Type 1 - concave upwards going from the smallest particle size followed by a slight curvature in the other direction at about the 20 mm particle size. The curves are well-graded with no gap-grading.

3. For variable proportions of constituent materials and a nominal maximum particle size of 75 mm, the greatest variation in particle size distribution occurs at the particle sizes passing the 20 mm sieve except where the crushed demolition waste has been passed through a single 50 mm screen. Where the crushed waste has been passed through a single 50 mm screen the greatest variation occurs at the particle sizes passing the 10 mm sieve. The greatest variation has a range of approximately 30%, for all sample groups, and gets progressively smaller as the particle size reduces.

4. The particle size distribution curves for all samples tend to converge at the smaller particle sizes (less than 5 mm).

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